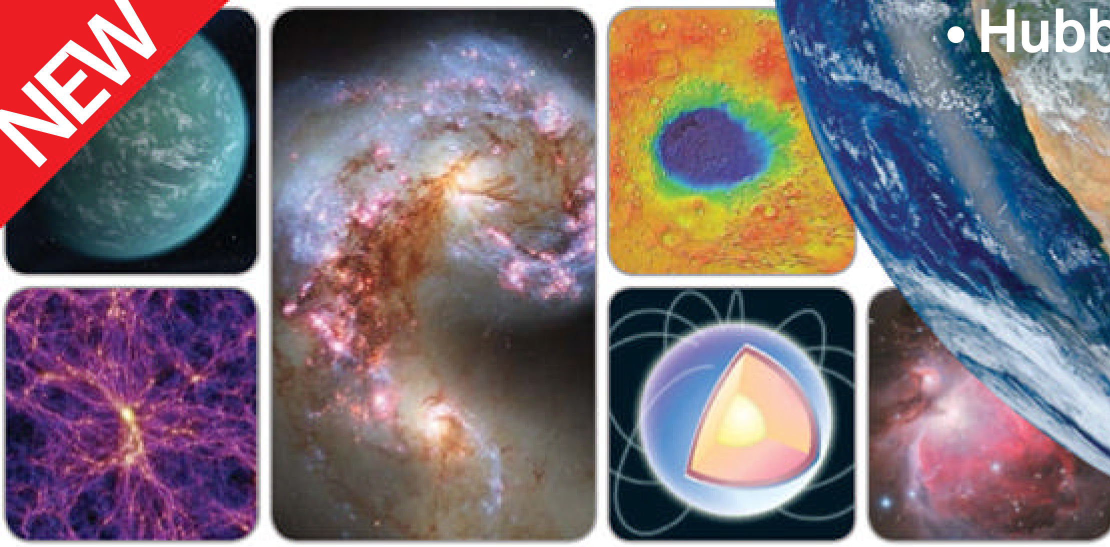
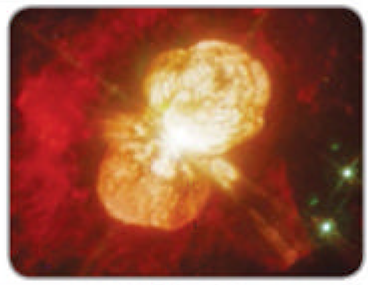
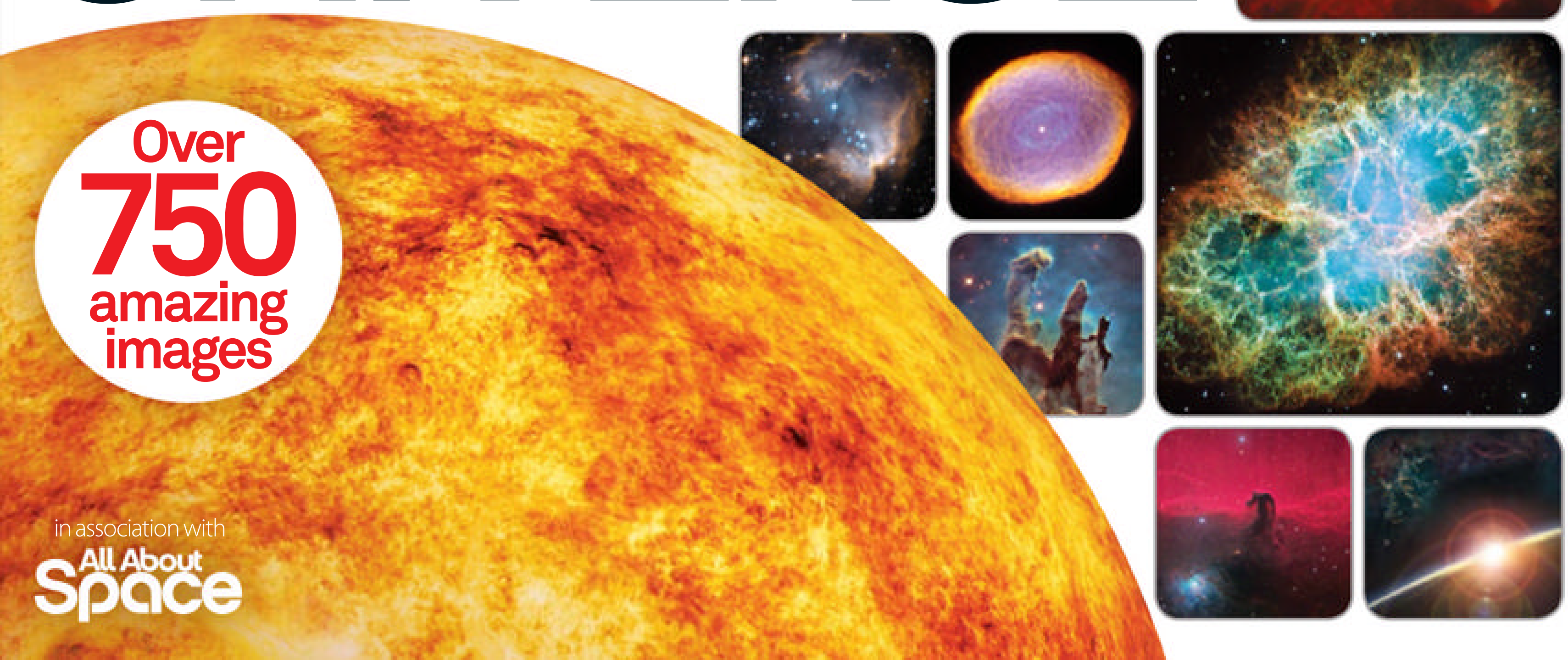


• Hubble's great discoveries
• Birth of a planet
• The Big Bang

NEW

COMPLETE HISTORY OF THE UNIVERSE





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If you've ever wondered how we came to be or what lies beyond our own Solar System, you'll find answers to those questions here. This book spans the vast unknown beyond our own home as well as delving into what we do know about how our planet was created. We have spoken to some of the most prominent experts in astronomy about the phenomena that we still don't quite understand, including dark energy, wormholes and antimatter, and fuelled debates about some of the most contentious subjects, including the elusive edge of the universe and the shape of space. You'll also find out about the most fascinating discoveries from the first 25 years of the Hubble telescope. Get ready for an epic journey, from the moment it all began, to the edge of infinity.

COMPLETE HISTORY OF THE UNIVERSE

Imagine Publishing Ltd
Richmond House
33 Richmond Hill
Bournemouth
Dorset BH2 6EZ
☎ +44 (0) 1202 586200
Website: www.imagine-publishing.co.uk
Twitter: @Books_Imagine
Facebook: www.facebook.com/ImagineBookazines

Publishing Director
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Printed by
William Gibbons, 26 Planetary Road, Willenhall, West Midlands, WV13 3XT

Distributed in the UK, Eire & the Rest of the World by
Marketforce, Blue Fin Building, 110 Southwark Street, London, SE1 0SU
Tel 0203 148 3300 www.marketforce.co.uk

Distributed in Australia by
Network Services (a division of Bauer Media Group), Level 21 Civic Tower, 66-68 Goulburn Street, Sydney, New South Wales 2000, Australia Tel +61 2 8667 5288

ISBN 978-1785460654

Part of the All About Space bookazine series

IMAGINE PUBLISHING

Contents

In the beginning

Secrets of the universe

Space science

"The black hole in the centre of the Milky Way galaxy is four million-times more massive than the Sun"

In the beginning

How the universe and everything in it came to exist

“When two spiral galaxies collide, it destroys their spiral structures and they merge into a giant elliptical”

22 How planets form

30 Creating a galaxy

Birth of the UNIVERSE

We speak to the scientists who explore the science and seek the answers to how our universe began

Meet the experts

Name: Richard Davis
Role: Professor
Head of technology at Jodrell Bank. Led his institution's involvement in the Planck mission.

Name: David Evans
Role: Professor
Leads the University of Birmingham team on ALICE at CERN's Large Hadron Collider.

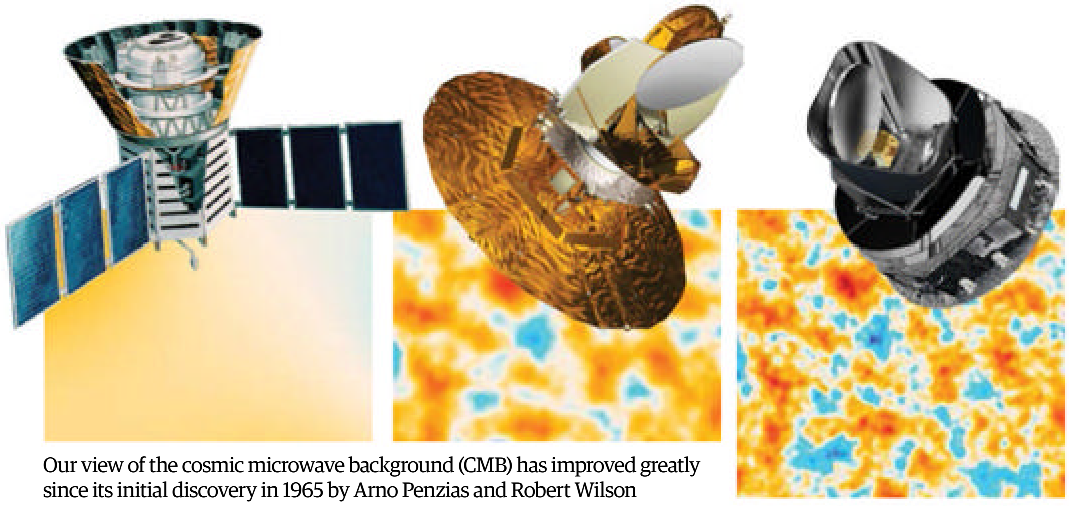
Name: Dan Coe
Role: Astronomer
Staff astronomer at the STScI, studying galaxy clusters, gravitational lensing and dark matter.

"The evolution of the world can be compared to a display of fireworks that has just ended; a few red whisps, ashes and smoke" **Georges Lemaître**

The universe almost seems to have come out of nowhere: a concoction of high temperatures and a thick gloop of exotic particles, which would go into an overdrive of expansion through several phases of varying conditions, to create the universe as we see it today, some 13.8 billion years later. The Big Bang, creator of time and space – or at least that's what our current understanding of how our universe sprang into existence leads us to believe.

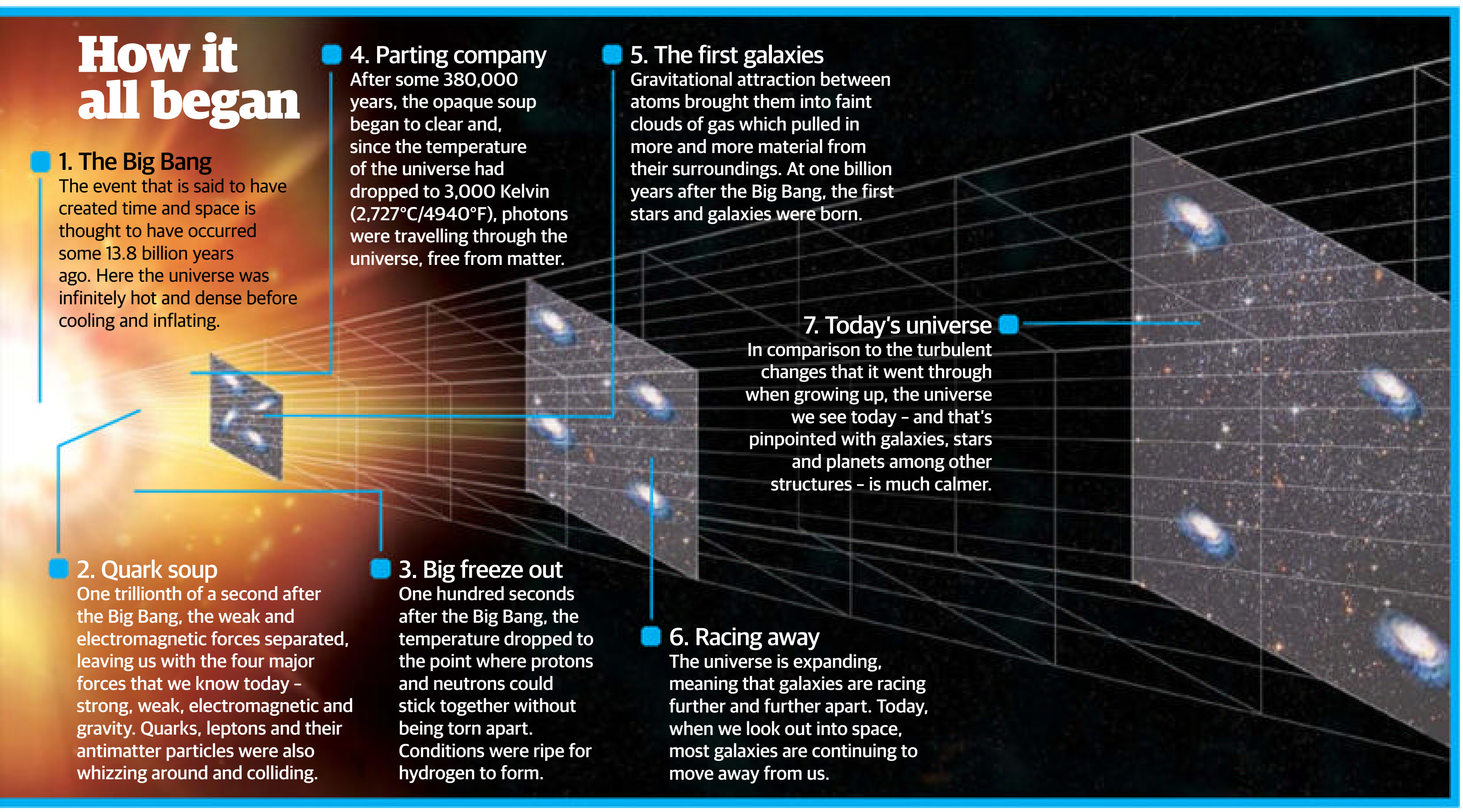
But what we have come to learn about the cosmos's somewhat mysterious past wasn't always as tacked down in the days of Georges Lemaître, who would later become dubbed the father of the Big Bang theory. What the Belgian priest, astronomer and professor of physics suspected in 1927, based on his solutions to Albert Einstein's equations, was that the universe must have sparked into life from a single point at the beginning of time before driving headlong into an expansion. "The evolution of the world can be compared to a display of fireworks that has just ended; some few red wisps, ashes and smoke," Lemaître said, on the subject of how we were thrown into existence. "Standing on a cooled cinder, we see the slow fading of the suns, and we try to recall the vanishing brilliance of the origin of the worlds." However, Lemaître wasn't recognised as the genius he was until later; he published his work in an obscure Belgian scientific journal where few scientists saw it. As such Lemaître's chance to go down in history was lost.

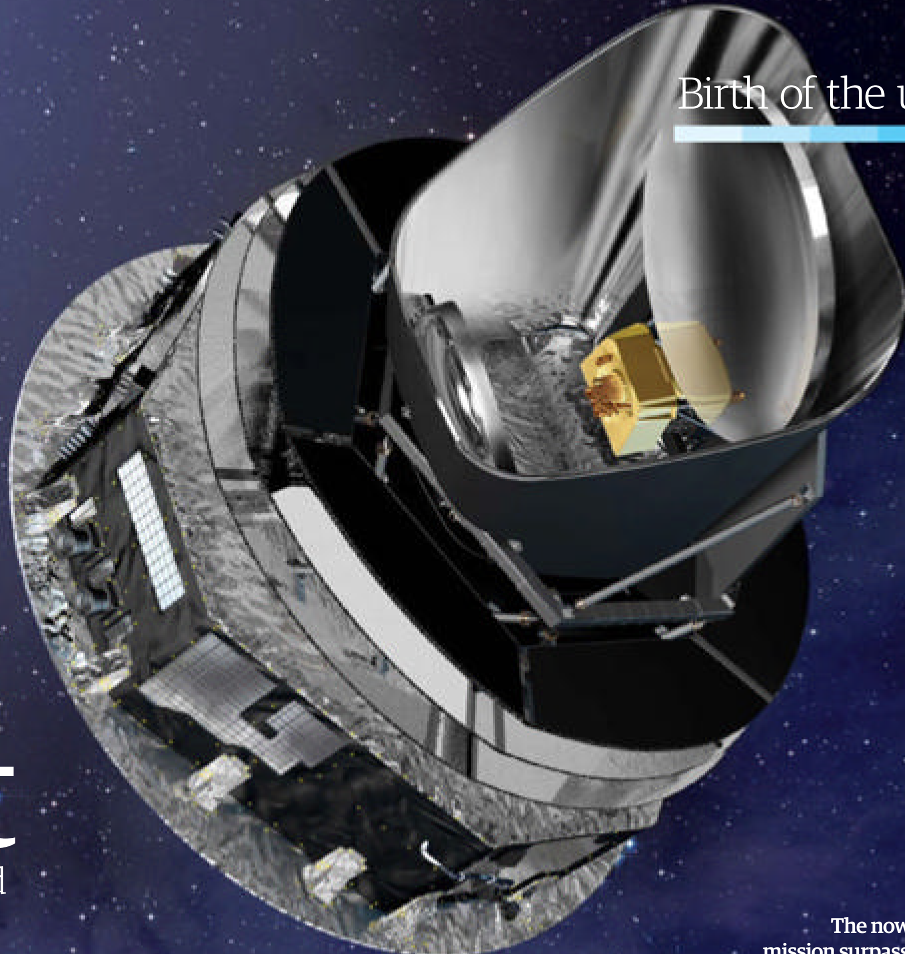
Instead, in America one astronomer in particular was gathering the data that would strongly support Lemaître's theory. Edwin Hubble and his assistant Milton Humason were busy at the eyepiece of a 2.5-metre telescope at Mount Wilson Observatory in California, surveying so-called spiral nebulae. These used to be thought of as part of our own Milky Way galaxy, but Hubble showed that they were island universes in their own right, galaxies like our own millions of light years away. He did this by measuring their redshift. This is just like the screaming pitch of a police siren racing past you. As the police car speeds towards you the Doppler effect causes the soundwaves to bunch up, making the pitch go up. As the police car moves away the soundwaves become more stretched and the pitch of the siren falls. In space, objects moving towards us have the wavelength of their light rays compressed into bluer wavelengths, which astronomers term blueshift, while objects moving away have their light stretched into redder wavelengths, hence redshift. Amazingly, Hubble found that almost all the galaxies had redshifts, meaning that they were all moving



Our view of the cosmic microwave background (CMB) has improved greatly since its initial discovery in 1965 by Arno Penzias and Robert Wilson

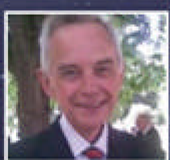
"The picture that the CMB provides is one of the baby universe – it's like we're looking back to when time and space first shuddered into existence"





The now-defunct Planck mission surpassed expectations in its study of the CMB

Seeing the start



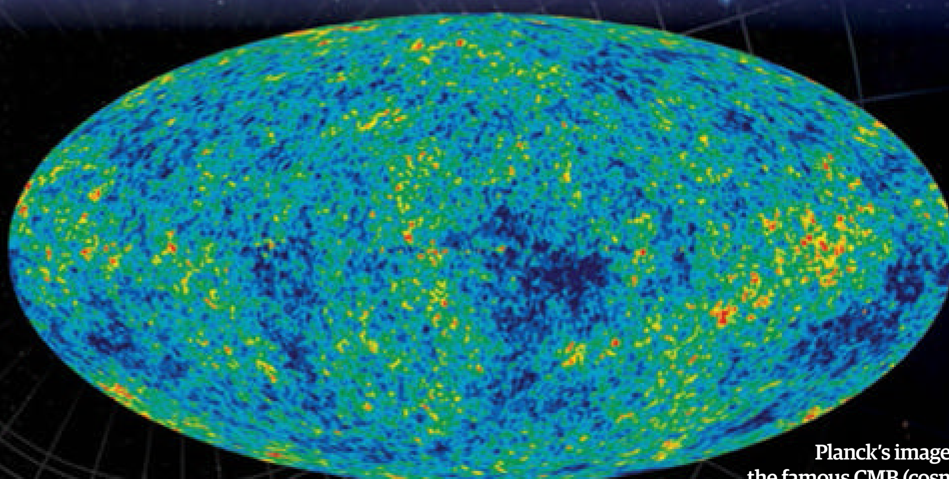
Astrophysicist Richard Davis explains how we measured the Big Bang

And then there was light. That's pretty much how our universe sprang into existence; as a point that contained everything and continued to expand through to today, building the first stars and galaxies and stretching light years of distance between them. Despite its name, the Big Bang wasn't some kind of explosion that spat out matter, energy, time and space. It is imagined almost like a balloon that continues to stretch, originally holding an incredibly hot and dense primordial soup that cooled and thinned out over the space of millions to billions of years.

As ever, such an event has opened up a whole deluge of questions. And the only way to attempt to look back in time is to lift missions off the ground to seek answers; providing us with the holy grail that is the snapshot of our newborn universe. Several missions have stepped up to the challenge, most notably the recently retired Planck mission – which communicated its final signal of what it knew about the ancient universe in October this year – under the joint efforts of ESA and NASA. Planck built upon and improved observations returned by its complementary mission, NASA's Wilkinson Microwave Anisotropy Probe (WMAP), which, after a good nine years of service, rests in its heliocentric graveyard orbit.

Planck's main aim was to measure the cosmic microwave background (CMB) – the afterglow of the Big Bang, that's encoded with how the universe appeared some 400,000 years after the event. And to get the best measurements possible, the mission had to be kept to freezing temperatures.

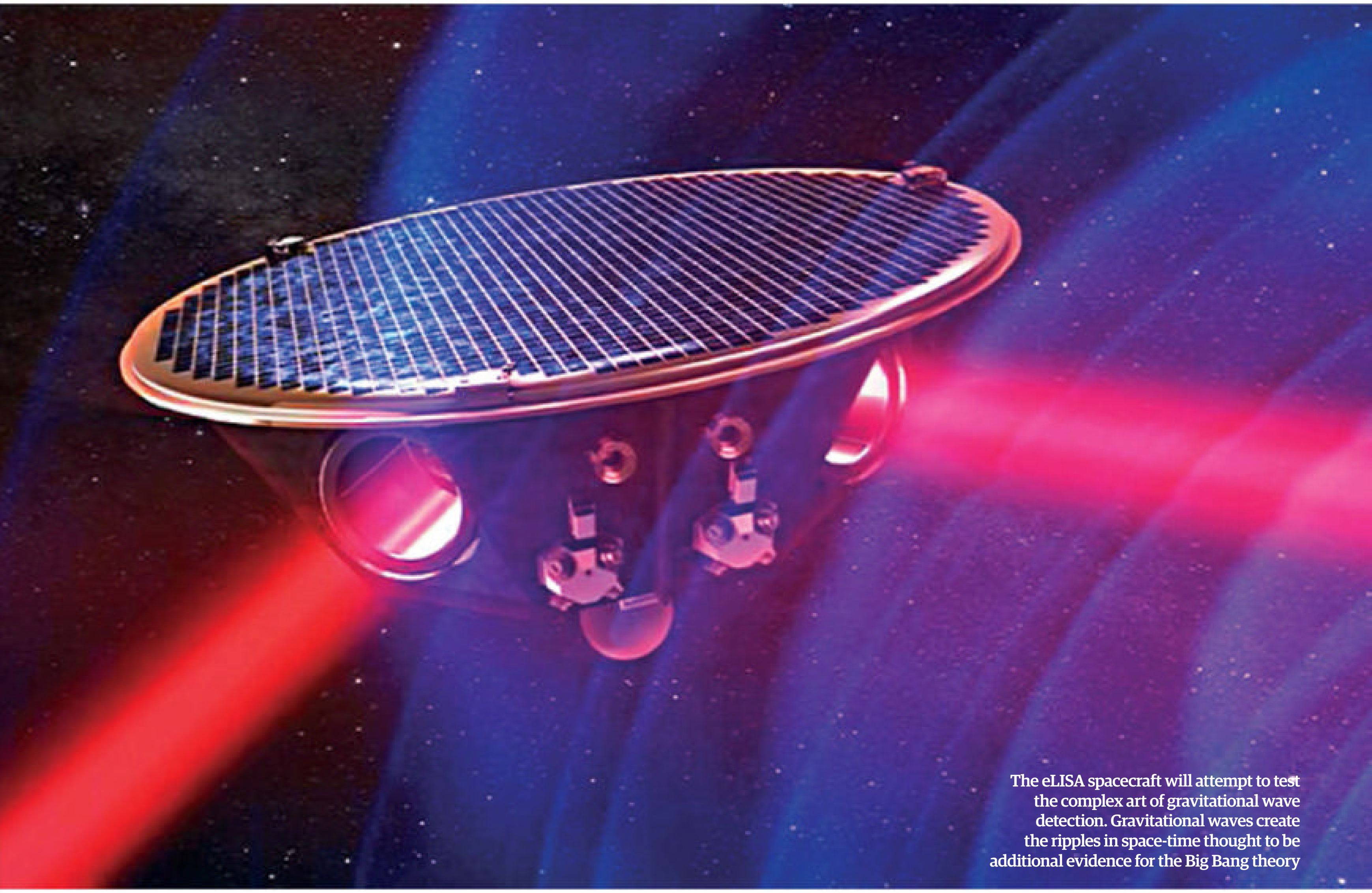
"[Planck had] a passive cooling and three refrigerators taking it to -273.05 degrees Celsius [-460 degrees Fahrenheit] which made it the coolest place in the universe," says the University of Manchester's Richard Davis, who led the UK's involvement in one of the instruments on board the craft. "It also had the lowest noise detectors ever made and are lower than anything detected before." An important feature of the CMB is that it is, by no means, smooth – it is a mess of different temperatures and it was from soaking up this relic radiation from its orbit around the Sun that Planck was able to pick out even the most subtle blips in temperature; something that Davis admits the mission did incredibly well. "The fluctuations go down to as low as 2 micro Kelvin," he says. "Planck surpassed its expectations and in some cases even exceeded its goals, so it has been stunning."



Planck's image of the famous CMB (cosmic microwave background)

> "Planck surpassed its expectations and in some cases even exceeded its goals, so it has been stunning" **Richard Davis**

Indeed, a couple of the many achievements that the space mission has in its arsenal is an all-sky survey that has provided us with our best view of the oldest light in our universe to now as well as a better measurement of the age of the cosmos, dated at 13.8 billion years old – 100 million years more than previously thought. And even though the mission has since been deactivated, Davis assures us that Planck could still wield the key to understanding more about our infant cosmos. "We will go on analysing the data for at least the next ten years so there is much to come," he says. "We will release the data in the next few years."



The eLISA spacecraft will attempt to test the complex art of gravitational wave detection. Gravitational waves create the ripples in space-time thought to be additional evidence for the Big Bang theory

away from us according to what became known as Hubble's Law. But if the galaxies are all moving apart, could they once upon a time have been much closer together, coming out of a big bang?

In 1931 Lemaître's work was brought to people's attention when Sir Arthur Eddington discovered it, but by then Hubble had already made his discoveries. At first Einstein did not believe it, but later changed his mind when he saw Hubble's evidence. A more vocal critic was astronomer Fred Hoyle at Cambridge University, who came up with the name 'Big Bang' in derision of the idea, and favoured his own Steady State model describing an eternal universe. The Big Bang name stuck, though.

Today, the Big Bang is a widely accepted theory. However, we don't have a photo album of how the universe grew from an infant into the veteran of cosmic evolution that it is today. Astronomers realised that they had to be resourceful, grabbing hold of any evidence that our universe was willing to give up and combining it with mathematical models. Of course, these clues are communicated to us in the cosmos's own way; ranging from the crackling of its background noise – the cosmic microwave background (CMB) – to gravitational waves that ripple between its many various galaxies.

The cosmic relic

And the universe is certainly telling us things about its past. The CMB was not the stealthiest of beasts when it generated interference on the experiments of Bell Laboratory astronomers Arno Penzias and Robert Wilson in 1965. Their device was called the Holmdel Horn Antenna, a radio telescope that listened in on the universe. Everywhere they pointed it, they detected an unwanted hiss, kind of like the low level of electrical noise that produces 'snow' on a TV screen. Only after they had ruled out every possible alternative did they finally accept that the unexplained signal could be coming from space. What's more, it was coming from all directions. They realised it was the sought-after cosmic microwave background radiation, that scientists suspected might exist. If our universe had a beginning then there was likely to be some kind of residue left over, flavoured in a static of microwave bands; a relic radiation, the cosmic microwave background. And at a temperature of 2.7 degrees above absolute zero (about -270 degrees Celsius or -460 degrees Fahrenheit) it's quite cold, making today's universe a chilly place to be as this radiation fills every corner of space. It was once quite hot, but has cooled as the universe has expanded.

The CMB was emitted about 380,000 years after the Big Bang, when temperatures in the universe fell to below approximately 3,000 degrees Celsius (5,400 degrees Fahrenheit). At this temperature atomic nuclei were able to soak up all of the free electrons that whizzed around the universe. With the electrons out of the way light and radiation were allowed to freely pass through space without bouncing off electrons, and this is the light that we see now as the cosmic microwave background. So although it doesn't quite show us the moment of the Big Bang, the appearance of the CMB is heavily influenced by what happened in the Big Bang, such as a brief period of inflation that moved parts of the universe apart faster than the speed of light. The picture that the CMB provides is one of the baby universe – it's like we're looking back to when time and space first shuddered into existence.

Mapping the sky

Penzias and Wilson were awarded the Nobel Prize for their discovery, but there was still much to learn about the microwave background – we wanted a map. The first mission to attempt this was the NASA-owned Cosmic Background Explorer (COBE) probe, which began snapping pictures of the CMB as soon as it was

launched in 1989. Offering four years of service, COBE announced the very first map of hot and cold spots within the CMB brought about by the early universe's gravitational field that would later form the seeds of gigantic clusters of galaxies that stretch for hundreds of millions of light years across the universe. COBE's lead scientist, George Smoot, also won the Nobel Prize, but hot on the heels of COBE came the Wilkinson Microwave Anisotropy Probe (WMAP). It boasted an improved resolution and got to work mapping the entire sky, logging the differences in temperature of the microwave radiation down to 25 millionths of a degree. What WMAP also uncovered told astronomers about the shape of the universe; they figured that since the boldest and brightest bursts in the map were a mere one degree across, then we must be living in a flat universe. By 2010, WMAP had sniffed out its last microwave, producing over nine years of information. WMAP had laid down some important foundations, making the mission a huge breakthrough. Meanwhile, as WMAP was put into retirement, a new space observatory was waiting in the wings, ready and willing to build on our knowledge of the early universe thus far – ESA's Planck. Operating in a range of microwave and infrared frequencies, the spacecraft promised an even higher level of accuracy, putting its instruments into overdrive in an attempt to lock down any answers given away by the deepest recesses of the universe. And Planck gave as good as it got from the universe, imaging the CMB in unprecedented detail. It might have ended its mission in October, but we are now the proud owners of a more accurate picture of an almost perfect universe as well as a more prominent point in time when the event began. The truth of the matter is that this microwave background isn't the only feature of the universe that's telling us how it began – there's more tantalising evidence and we're making sure that we're taking advantage of it.

"Planck imaged the cosmic microwave background in unprecedented detail"

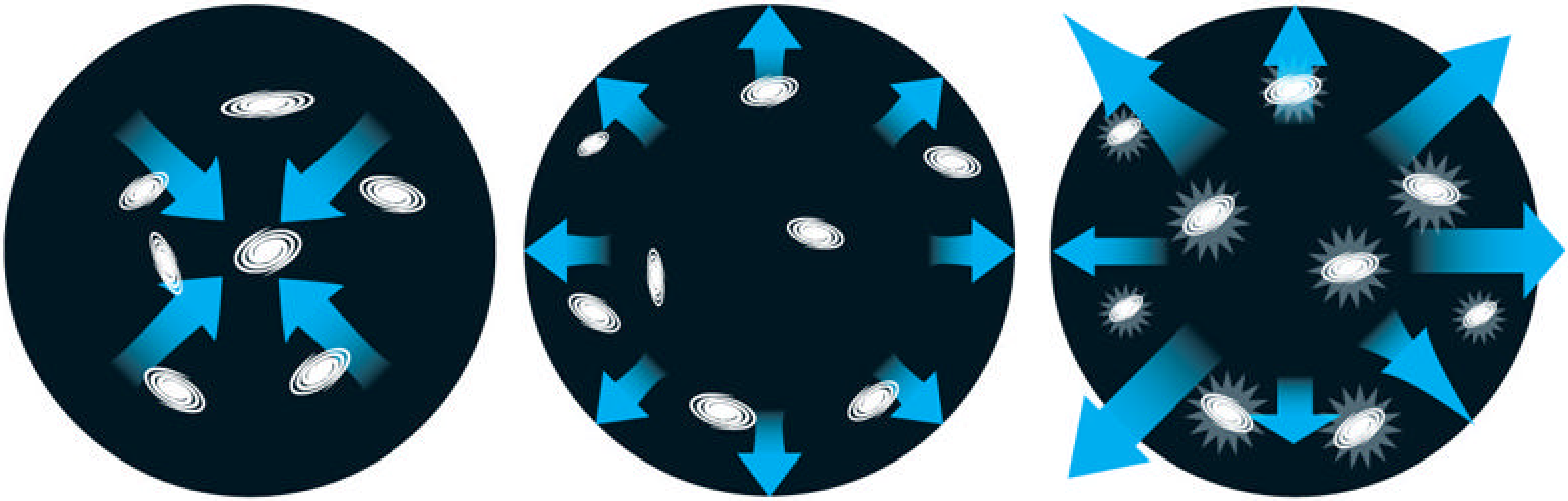
And these extra telltale signs are the ripples in space-time – gravitational waves. These elusive oscillations represent one of the missing pieces of Einstein's theory of relativity. Gravitational waves can be created by all kinds of massive objects, but some were also believed to have formed in the Big Bang and could still be rippling through the universe today. The problem is that it's not easy to directly detect them but their elusive behaviour means that the universe also has difficulty influencing them under its will. This is good news for us as they are the only known form of information that's able to reach us undistorted from the time of the Big Bang. The trick is catching them as you need incredibly sensitive detectors. Not put off by their shyness, scientists have been intent on pinning these waves down. Unlike the common electromagnetic radiation that we're used to, gravitational waves, which are the result of massive events such as the merging of supermassive black holes, like to work their way through all types of matter – whether it be gas or dust.

Previous attempts to grab gravitational waves by the tail, which includes the likes of a large-scale experiment called the Laser Interferometer Gravitational-Wave Observatory (LIGO), haven't gone unnoticed but have sadly been fruitless. We need something better and while 'advanced LIGO' is in the works for next year ESA has been thinking outside our Earth's atmosphere and straight into the thick of space. The plan is to build a mission that has the ability to deal with such a slippery character. Scientists think they might have that pegged with the help of a planned mission, the evolved Laser Interferometer Space Antenna (eLISA) – a large-scale space mission that will not only detect this elusive phenomenon, but will also be able to survey the entire universe directly with these waves, giving us more information on the formation of galaxies, how stars grow and the early universe. Planned for launch in the future, the people behind the craft proudly proclaim that it will also be able to tell us more about the structure and nature of space-time. There will also be the opportunity for uncovering more about black holes as well as other unknown objects. Before it can begin to achieve its goals, an advance scout named LISA Pathfinder will launch in 2015, paving the way for eLISA to test the complex art of gravitational wave detection.

As we understand it, from the reams of data brought about by the teamwork between missions and theories, we think we've put together a pretty robust photo album – or timeline – from the universe's

How it will end

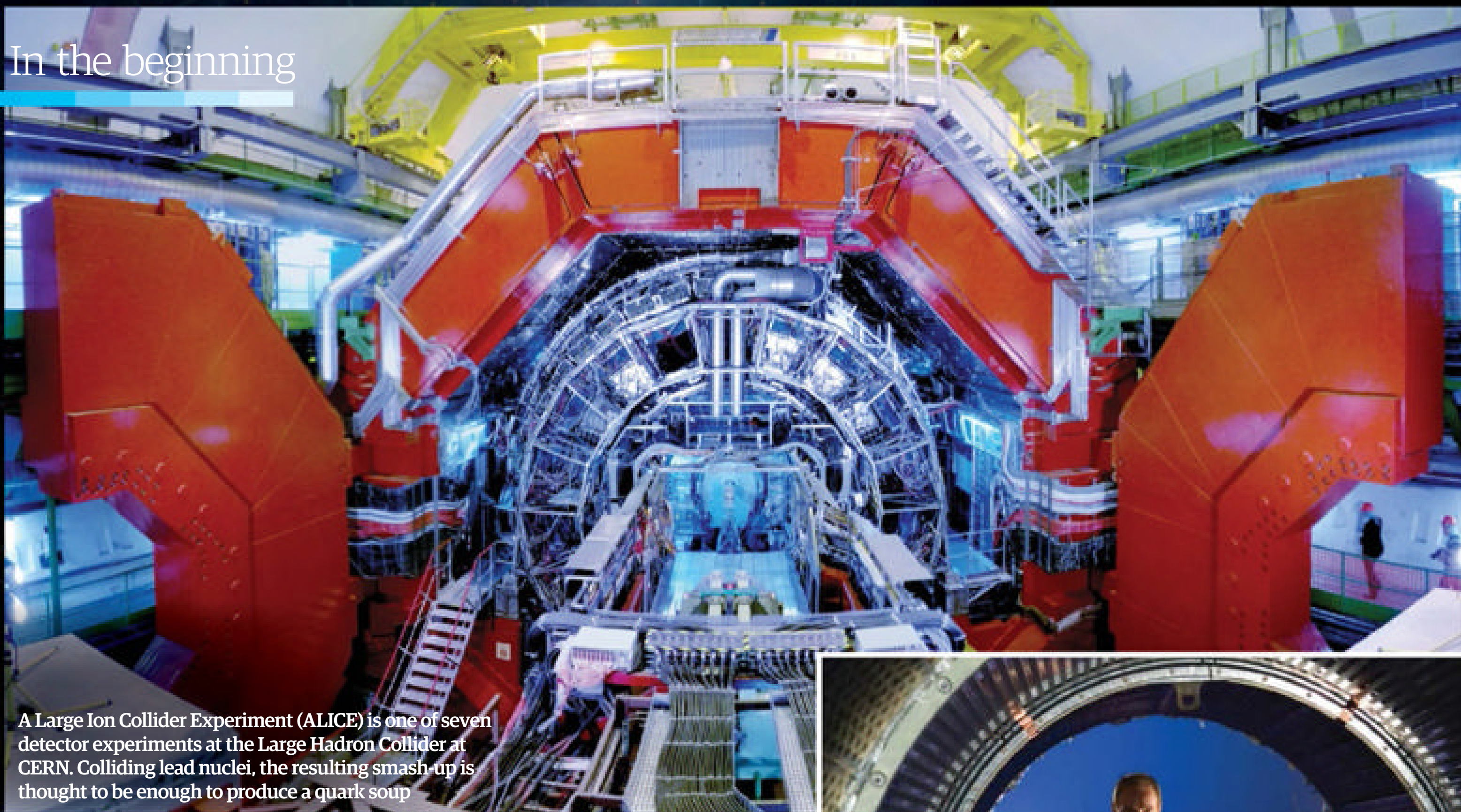
There are thought to be three possible ways the universe will end. One is the Big Crunch, where gravity takes over and compresses it to one point. Another is the Big Rip, where the expansion of the universe gets faster until galaxies, stars, planets and space itself is torn apart. Then somewhere between these extremes is the likely scenario where the universe's expansion is not great enough for a Big Rip and gravity is not strong enough for a Big Crunch. Instead the universe will continue to expand, growing cold and lifeless – the Big Freeze.



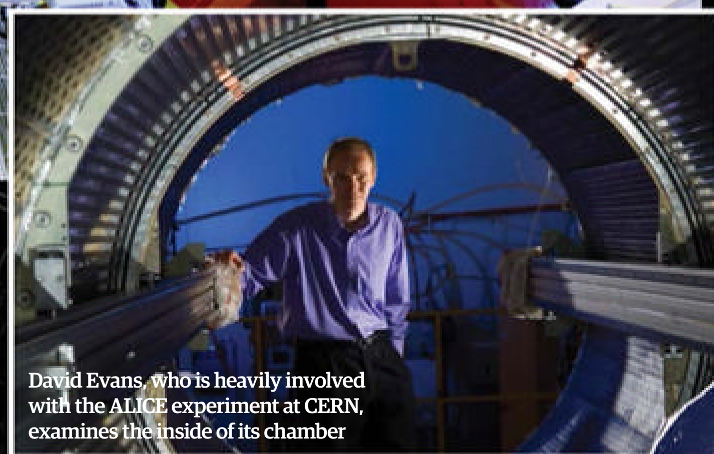
Closed universe
The density of the universe is more than five atoms of hydrogen per cubic metre. There's no repulsive effect of dark energy and gravity eventually halts the universe's expansion. With contraction, all the matter in the universe collapses to a point – the Big Crunch.

Open universe
If space is open and curved, the universe will continue to expand forever. Dark energy will help to drive the expansion. The result? Heat death, the Big Freeze or the Big Rip is imminent. Here the universe's density is less than the critical density.

Flat universe
With no dark energy, a flat universe will expand forever at a decelerating rate. With dark energy the expansion initially slows thanks to gravity, then speeds up. The universe's ultimate fate is the same as if it were open. Density and critical density are equal.

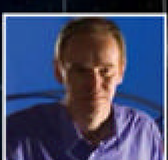


A Large Ion Collider Experiment (ALICE) is one of seven detector experiments at the Large Hadron Collider at CERN. Colliding lead nuclei, the resulting smash-up is thought to be enough to produce a quark soup



David Evans, who is heavily involved with the ALICE experiment at CERN, examines the inside of its chamber

Re-creating the Big Bang



Professor of high energy physics David Evans is making baby universes

Tucked away in the highly populated city of Geneva in Switzerland, the particle-smashing Large Hadron Collider (LHC) – built by the European Organisation for Nuclear Research, which is more commonly known as CERN – has been hard at work accelerating particles to breakneck speeds close to the speed of light. The aim? To attempt to re-create what the early universe might have been like just a few minutes after it was born. The particle accelerator, which houses two detectors dedicated to pinpointing the moments during our universe's growth (LHCb and ALICE), works as a Big Bang-making machine. The differences are that this 'explosion' is on a much smaller scale and scientists have a bit more control over it.

For ALICE, the aim of the game is to smash particles of lead into each other to create a plasma that existed some ten millionths of a second after the Big Bang. "Lead atoms have all of their 82 electrons stripped off and the positively charged nuclei are accelerated to over 99.9999 per cent the speed of light in the LHC," says the University of Birmingham's David Evans, who leads the team working on the ALICE experiment. "The lead nuclei then smash together inside the giant ALICE detector and, for a brief instant, create a super hot and dense sub-atomic fireball."

What these results show is that the tiny fireballs – which are a lot smaller than a single atom – that Evans speaks of, reach temperatures of a scorching six billion degrees Celsius (10.8 billion degrees Fahrenheit). That's over 300,000 times the temperature of our Sun and, what's more, the density that results is 50 times that of a neutron star. "Such extreme temperatures and densities would have last existed just about a millionth of a second after the Big Bang and, under these conditions, protons and neutrons (which make up the nuclei of atoms) 'melt' into a soup of fundamental particles called quarks and gluons," adds Evans. "This primordial soup is called a quark-gluon plasma."

Evans believes that the plasma they produce in ALICE is fairly representative of the early gloop of the early universe. "However, the fireball we create is much smaller than the one in the early universe and, hence, will cool much quicker," he says, before adding that the results brought about by the detector are indicative of breakthroughs in our understanding of the early cosmos. "Although it's still early days," Evans tells us, "our results show that the quark-gluon plasma seems to behave like the most perfect liquid ever produced. So it seems the universe was born of a perfect liquid."

Another surprise was just how strong the forces are in this plasma where high-energy particles, usually found to barge their way through metres of thick detector material, find themselves absorbed in incredibly small distances not much bigger than the nucleus of an atom.

At the moment, the LHC has been shut down for several important upgrades but, when it's up and running again in early 2015, Evans and his team plan to put it to even more good use. "We will be able to collide lead nuclei at double the energy, creating even hotter and denser fireballs," he explains. "We are really just at the beginning of an exciting endeavour to discover the properties of the quark-gluon plasma, I am expecting to find many surprises along the way."

Meanwhile, the team behind the LHC experiment will get back to trying to work out why there were unequal amounts of antimatter and matter. Of course, the Large Hadron Collider has also done us proud by unearthing the Higgs Boson – the particle that is responsible for all of the mass in the universe.

"The quark-gluon plasma seems to behave like the most perfect liquid ever produced" **David Evans**

birth all the way through to its 13.8 billion-year-old self. Shortly after its sudden appearance, there was nothing except for a plasma soup. The universe was incredibly hot with particles of both matter and antimatter – the opposite of matter – rushing apart in all kinds of directions. Then it began to cool, producing equal amounts of matter and antimatter, which swiftly annihilated each other. Lucky for us, for some reason that nobody yet understands, there was extra matter leftover and, as the universe began to peter out, cooling further, particles – the building blocks of matter – began to take shape. The first stars formed around 400 million years after the Big Bang, followed by the first galaxies – the oldest galaxies we have seen so far are a whopping 13.2 billion years old.

As much as we are sure the Big Bang happened, the nature of the universe still raises a host of existential questions. Where did the universe come from? Why did it appear in the first place? Why was there more matter than antimatter in the early universe? Why is dark energy causing the expansion of the universe to accelerate? What we do know, however, is that the Big Bang was not an 'explosion' into anything, it happened everywhere, which is why everywhere is filled with the CMB. And we also know that the ultimate destiny of the universe depends on what wins the great cosmic battle over the fate of the cosmos: will gravity tug the universe back, or will dark energy keep it expanding forever? These questions remain unanswered.

Missing pieces

It might be the king of theories when it comes to explaining the birth of the universe, but the Big Bang theory still hits a few snags.

1. Disappearing antimatter
In the beginning, there were equal amounts of matter and antimatter – two materials that, when they come together, annihilate each other. Why, then, does our universe now contain mostly matter?

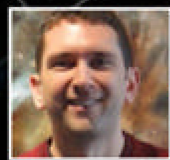
2. The horizon problem
Are the widely separated regions of the sky too far apart to communicate with one another? If they're unable to communicate, scientists are unsure how they know to have the same temperature.

3. The flatness problem
Evidence suggests that the present universe is pretty much flat. Experts think that its current form is a very unlikely result of the universe's evolution from the Big Bang.

4. Galaxy formation
Random bumps in the expanding universe may not be enough to form galaxies. In a rapidly expanding universe, gravitational attraction loses the fight and is too slow for these structures to form.

5. The monopole problem
The Big Bang predicts that a large number of 'magnetic monopoles' should have been made in the early universe. But they've never been seen, so, if they exist at all, they're much rarer than predicted!

Observing the aftermath



Astronomer Dan Coe is looking at the Big Bang's deep space consequences

Around 13.8 billion years later, here we are. As the stars, galaxies, planetary systems and other bodies are silently suspended in an endless void of blackness, it is difficult to believe that there was a time in the universe's life that conditions were chaotic and ever-changing. But there is evidence everywhere and in all directions; the Hubble Deep Field – snapped by the long-serving Hubble Space Telescope – made sure of that.

"The Hubble Deep Field revealed distant galaxies which appear very different from nearby galaxies," explains Dan Coe, an astronomer at the Space Telescope Science Institute in Maryland, USA. "They are generally smaller, more clumpy and less orderly than nearby galaxies and yet to form spiral patterns or settle into elliptical balls."

Constructed from a series of observations over a period of ten days, this tiny snapshot – which is equivalent in size to a 65-millimetre tennis ball held at a distance of around 100 metres away – holds 3,000 objects, most of which are galaxies. Several of these structures are among the youngest and most distant known – providing a pathway that allows us to look back to when the universe was young. "Distant galaxies appear redder," says Coe. "This 'redshift' is due to the expansion of the universe. As the universe expanded over billions of years, it stretched light along with it into longer, redder wavelengths. Ultraviolet starlight emitted billions of years ago from distant galaxies has been stretched along its journey to our telescopes to red or even infrared wavelengths."

The advent of a new infrared camera on board Hubble saw astronomers take the opportunity to look into the universe's past and to reveal ever more distant galaxies with greater redshifts. "Even if our eyes were as large as Hubble's, these galaxies would remain invisible to us," says Coe. "We believe the most distant galaxy detected in the Ultra Deep Field dates back to 500 million years after the Big Bang, over 13 billion years ago."

But Coe and his colleagues are looking further still. "The Hubble Ultra Deep Field was about twice as big as the original," he says. "We are now embarking on a large new Hubble programme to observe 12 more Ultra Deep Fields in different parts of the sky." The programme Coe is referring to is a new venture called Frontier Fields and will tell us how similar other patches of sky look to the Ultra Deep Field; that way we can confirm whether the cosmos is expanding in all directions. "It will also use cosmic zoom lenses known as gravitational lenses to magnify the distant universe and observe even more deeply." The Spitzer and Chandra space telescopes will also take images of the Frontier Fields, in infrared and X-ray.

Coe reminds us that terrestrial telescopes that have surveyed wide areas of the night sky have found that the universe looks similar in all directions. "Over billions of years, gravity has woven a 'cosmic web' of dark matter that funnels gas in to form stars and galaxies and draws galaxies together to form large clusters of galaxies," he explains. "The original Ultra Deep Field may have landed on a dense cosmic knot or a cosmic void. That's why we need more Ultra Deep Fields, to sample more of the distant cosmos."

> "The Hubble Ultra Deep Field was about twice as big as the original"
> **Dan Coe**

Coe and his colleague Jennifer Lotz, an assistant astronomer also at the Space Telescope Science Institute, who leads the Frontier Fields programme

Big Bang: not just a theory

It's the biggest announcement in science since the Higgs Boson: We speak to one of the founders of the project that recently confirmed the Big Bang theory of cosmic inflation

INTERVIEWBIO

Prof James Bock

Professor Bock is co-leader of BICEP and, as one of the founders, has been with the project since its inception in 2001 over a game of tennis with astrophysicist Professor Brian Keating. He has worked as a researcher at NASA's Jet Propulsion Lab and specialises in experimental cosmology at the prestigious California Institute of Technology (Caltech).

The Dark Sector Laboratory is home to the BICEP2 telescope (left) and South Pole Telescope (right)

"It gave a factor of ten improvement in how quickly we could make these measurements… BICEP2 was in the field for three years, so if we had kept going with BICEP1 it would have taken 30!"

Could you tell us a bit about the BICEP2 project? What exactly was it you originally set out to do? How did it differ from the original experiment, BICEP, that if followed?
BICEP2 is a step in a larger programme. We originally started an experiment back in 2001 called BICEP, which was designed to go after this polarisation signal exclusively. The idea emerged from my talking with a post-doc in the group, thinking that this would be an interesting signal to go after. The original BICEP experiment was this small, custom-designed telescope with an angular resolution of about half a degree – a similar size to the full Moon and enough sensitivity to resolve the expected structures. It was really a specialised experiment with a lot of light-gathering power, which meant that, in spite of the small telescope diameter, it had an enormous field of view. The focal point of the telescope is just packed with detectors to give it maximum sensitivity.

Is that what distinguished the BICEP instruments?
With BICEP1 we thought that was a very novel approach, as it hadn't been done before. I was also working on the next generation of detectors – futuristic devices that didn't exist at the time, called antenna-coupled bolometers. We designed the experiment so that we could put in these detectors when they were ready, but we used somewhat old-fashioned detectors.

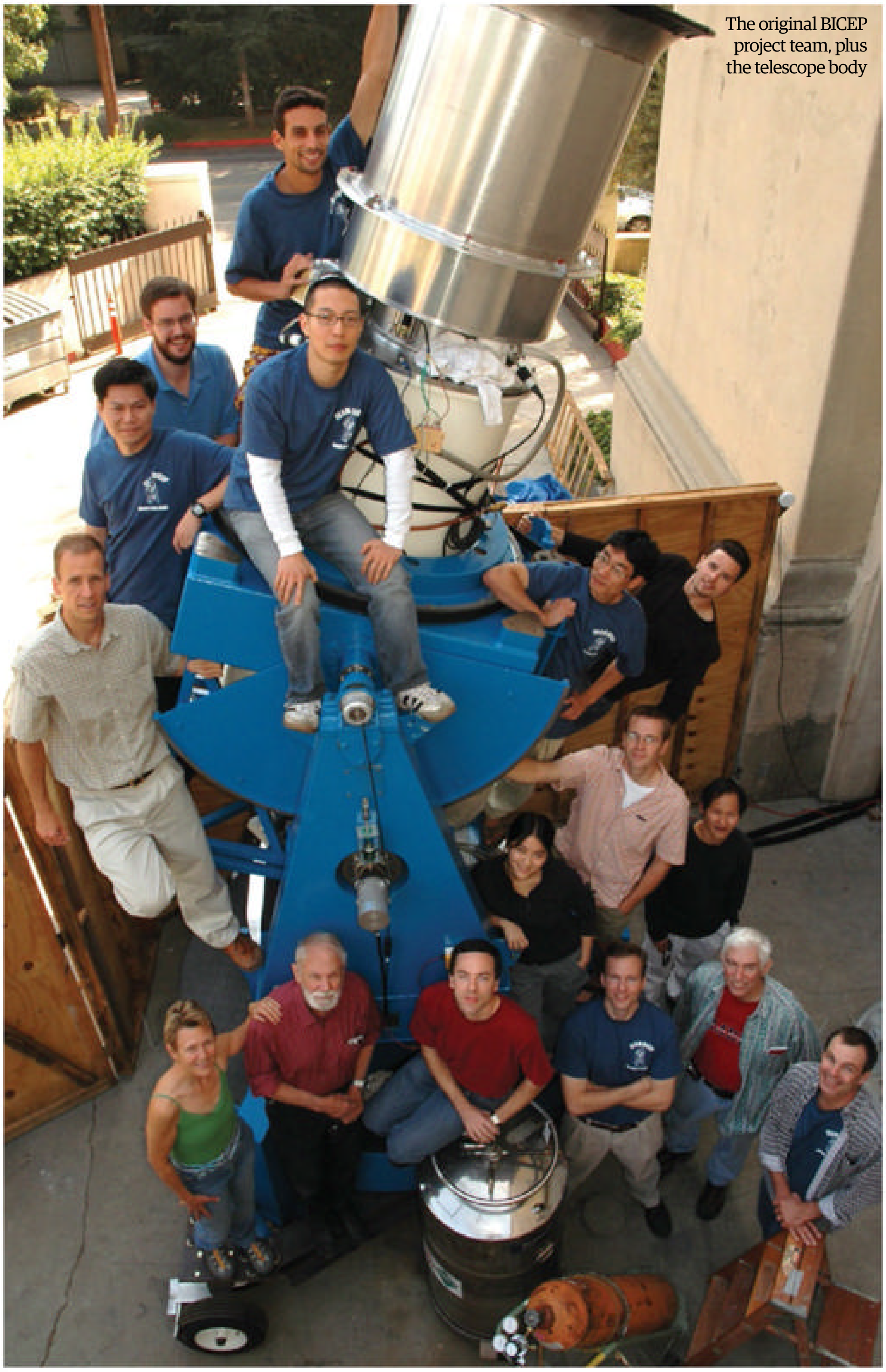
BICEP1 got out into the field in Antarctica and observed for three years, but it didn't have the sensitivity to detect the signal that we're recording now. Then, after BICEP1, we fielded BICEP2 and the only difference really was the fact that we used these new detectors. It gave us a factor of ten improvement in how quickly we could make these measurements. That makes a huge difference: BICEP2 was in the field for three years, so if we had kept going with BICEP1 it would have taken 30 years

You were based at the South Pole. Could you have made these crucial observations anywhere else?
Well, it's possible that you could observe at different places on Earth, but for us the South Pole is really perfect. It's got a remarkably stable atmosphere. The first thing you worry about when it comes to millimetre wave observations is water vapour in the atmosphere, so you want to go to a high site. On Earth, a high site in the South Pole is good for that, as it has about [3,048 metres] 10,000 feet of elevation. Also, because the air's so cold there, most of the water vapour has frozen out of it. The skies are very transparent and it's also very stable, because at mid-latitudes the atmosphere gets churned up by diurnal variations of sunlight and dark. Also, at the poles the Sun goes down for months at a time, so the atmosphere's very stable.

The other thing about the poles is that the field we want to observe is always up. The sky just goes around in a circle all the time – so if we move our telescope with it we can observe it all the time. Finally, the South Pole is all set up for scientific observation; there are facilities, there's a gym… it's really a top-notch place from that viewpoint as well.

When you started using BICEP2 you discovered a signal that was much stronger than you expected. What did you expect to see and why was this gravitational wave signature such a surprise?
I think there are two things: first there is the indirect recognition from the Planck satellite. It's not using polarisation, but rather the structure of the intensity variations in the background… It could have been telling us something about inflation, it may be that statistically, but this is something that gets resolved, worked out. There was that result going in [to BICEP2]. Then there was this expectation in the community, and I'm as subject to this as anyone, that we should really be designing these experiments to go very deep to look for the signal.

So, we were all geared up to even more powerful experiments, to find incredibly low numbers. When the results initially came out – I became aware of it about a year ago from our data – I was sceptical. We spent the past year just looking at every possible way


The original BICEP project team, plus the telescope body

"We spent the past year looking at every possible way the instrument could produce a false signal. We had many turns and zig-zags... but every time the data would get more consistent"

the instrument could produce a false signal. We had many turns and zig-zags through this process, but every time we would come up with a mechanism, generally we would find that after going through it, we would learn a few things about the data and it would get even more consistent. The data would still be present – we were able to find an explanation for the signal. The thing that pushed us over was that we compared our data with BICEP1, which itself doesn't have the sensitivity to produce the signal, so we could do a cross-comparison. That cross-comparison was consistent with what we were getting.

So, it gradually dawned on the team that you might be on to something? How exactly did that feel, being so close to something so significant?
Well, you know, it's funny how these things emerge and, as I said, people have different reactions... We have four leaders of the overall programme who would sit down and talk every so often just among us asking, 'Do we believe it?'

Different people would have different levels of confidence. But that wasn't good enough – just to sample people's opinions, so we'd ask, 'If you think this is wrong, what specific test should we do next?' Then we would talk about the strategy for the next two weeks, discussing what tasks we could do that would confirm or open up a line of inquiry that would tell us what was happening. We just systematically went through all the objections and thoughts of our team, taking one at a time.

The funny story is that last year, in the spring, we had actually been trying to get an upper limit paper out because we had all this great data. We just assumed that we'd be putting a maximum value on the signal level and we couldn't get any answer that was just noise. We kept seeing this extra signal – it was statistically significant and we didn't see it in any of our other tests and actually, we were pretty frustrated that we had this signal and we couldn't get rid of it! Then we had this meeting where we compared our data with [findings] from Caltech and they agreed. Suddenly, for me it was this watershed moment: 'It's real!' I thought.

What exactly is B-mode polarisation and how did it help you to finally verify the theory of cosmic inflation and in so doing the Big Bang theory?
You can mathematically decompose a pattern of polarisation into two kinds. There's one called the E-mode pattern, which has a particular kind of signature... it doesn't have a curl. You can take any pattern of polarisation and it has an E-mode part, which is basically curl-free and a B-mode part, which only has curls.

Cosmic inflation sets up density waves that are a big source of the polarisation pattern in the microwave background. In fact, that's most of the signal we can actually see – mostly E-modes. Density waves cannot make a B-mode pattern, so if you see one it cannot be made by density waves: you're led to a source that has a handedness. Gravitational waves have left- and right-handedness. Scientists have known about this since around the 1990s and there have been a number of papers released proposing that we look for this B-mode pattern as a signature of inflationary gravitational waves.

How can this signal be recognised for what it is after such a long time?
The gravitational waves from inflation – they're kind of the analogue of the microwave background. The microwave background is this afterglow of the Big Bang made up of the oldest photons we can see, it's just that they're scattered. They were created in the early universe at an earlier time from matter-antimatter annihilation. At that time the universe was very hot and those photons were bouncing around against the electrons.

Then there was this time when the universe cooled down as it expanded, when the free electrons paired up with protons and the neutral hydrogen. Next the universe became transparent. So ever since that time, which was about 380,000 years after the Big Bang, the universe was pretty much transparent to optical light. That's what we're seeing in the background, but we can't see the earlier times directly because the photons have been strongly scattered. Gravitational waves are kind of the same analogue; they're a background made from the early universe. They're much harder to detect than photons and haven't been observed directly – we've inferred them from things like orbiting pulsars.

These gravitational waves in the background don't interact with the universe from the time that it was created to a very good approximation. So it's basically been free-streaming to us from the time that inflation happened, some 10^{-32} seconds after the Big Bang. If we could see these gravitational waves directly, presumably we would detect them and we could map out their structure and all that.

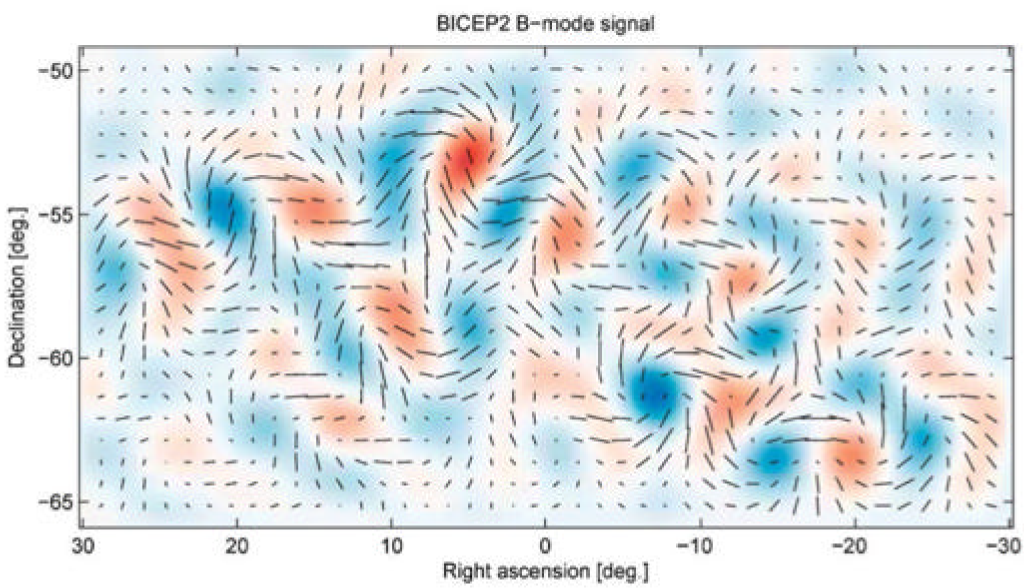
By using the microwave background, we're basically using the universe as a gravitational wave-detector. The squeezing and stretching of the gravitational waves produces this polarisation pattern that we're seeing in the background.

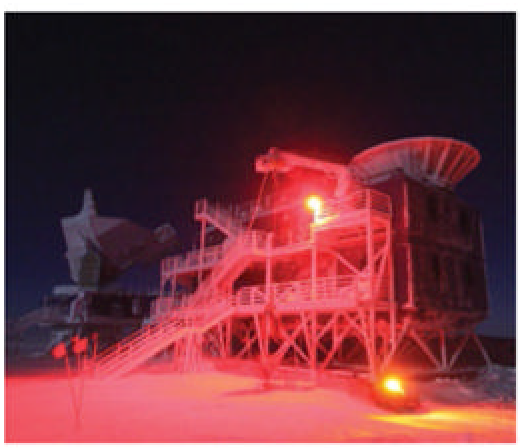
Where do you go with BICEP now that you have made the announcement?
In the near-term the field is going to be active trying to test our instrument to see if it's verified or not. We'll be participating in that as well.

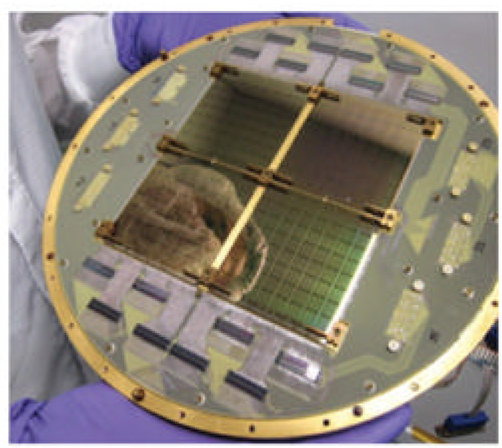
There's been a lot of talk of Nobel Prizes in the media – would you care to comment on that?
[Bock laughs] No.

Will you be going back to the South Pole for further work any time soon?
Yes. Right now the Sun has set in the South Pole, so we're in winter mode. We're collecting data with the Keck Array, two focal points running at a different colour, at 95 gigahertz instead of 150 gigahertz. That data, in two months, should be more powerful than what we used in our paper.

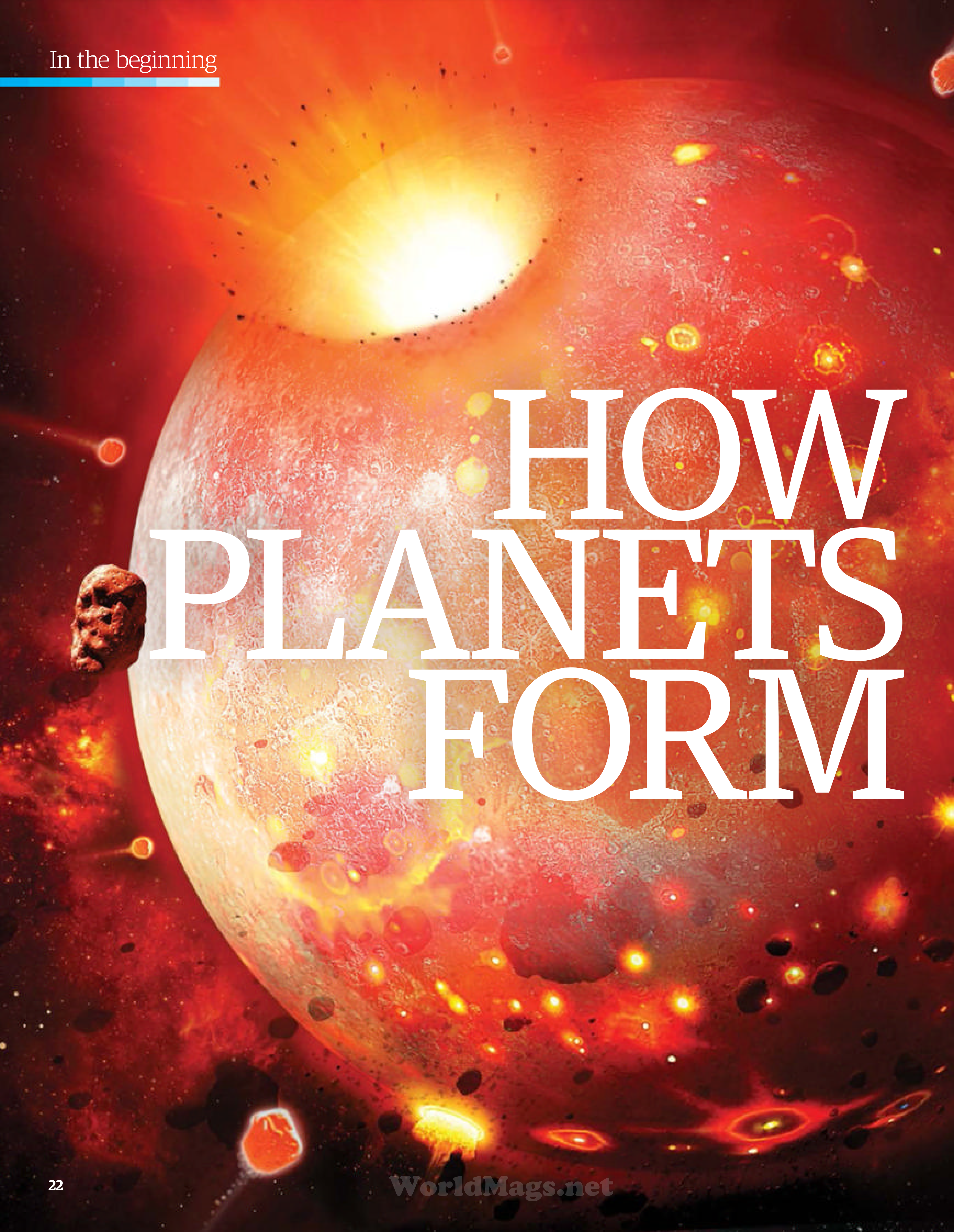
In October 2014, the season opens again for summer time and we have a new experiment called BICEP3, which will be the most powerful instrument of its kind. Once the station opens we basically have from mid-October until February to bring our experiment down, get it running, calibrate, test and prepare it for cosmological observations. In the meantime we will be servicing and calibrating the Keck Array. It's going to be a busy Antarctic summer. I'm really looking forward to it. ■







Clockwise from the top: A graduate tests the electronics of the BICEP2 instrument inside the Dark Sector Laboratory; the BICEP2 B-mode signal, showing a signature curl that verifies the theory of cosmic inflation; the focal plane of the BICEP2 instrument, which uses the highly specialised bolometer detectors Professor Bock worked on at JPL; liquid helium, coolant for the superconducting BICEP2 telescope, is delivered to the laboratory during the grip of the freezing Antarctic winter where in some areas darkness can preside for six months



HOW PLANETS FORM

Discover how our home, along with our Solar System neighbours and every other planet in the universe, was born from a chaotic cloud of dust and gas

In a sense, planetary birth is a side effect of a larger birth: the formation of a star. Stars form from nebulas, massive clouds of gas and dust dominated by hydrogen and helium. Now and then, a disturbance in a nebula concentrates an area of gas and dust into a denser knot of material. If the knot is big enough and dense enough, it will exert enough gravitational pull to collapse in on itself. The huge volume of super-dense gas concentrates at the knot's centre, and the gravitational energy heats it up to form a protostar. With sufficient mass, the energy of the protostar increases, eventually initiating a nuclear fusion reaction and graduating to a proper star.

Meanwhile, according to the solar nebula theory, surrounding gas and dust form a protoplanetary disc, or proplyd, around the protostar. When the protostar first begins to form, the surrounding material is still an unordered, slowly churning cloud. But the protostar's growing gravitational pull accelerates the cloud's movement, causing it to swirl around the centre. As the swirling mass speeds up, it flattens out, forming a thin disc, packed with all the material that will eventually coalesce into planets.

As well as explaining how planets form, the solar nebula theory also explains why solar systems take the form they do. The planets all revolve in the same direction around a central star, in the same plane, because that's how the material disc originally swirled around the protostar.

Exactly how it all comes about is still up for debate, and there may actually be many different planet formation processes. The prevailing understanding, called the accretion model, is that planet formation begins when individual bits of matter in the disc clump together into bigger chunks. The accretion model seems to be correct at least in the case of rocky terrestrial planets, like Earth and Mars, which form from silicates and heavier metal, such as iron and nickel.

Astronomers generally agree that a planet like ours begins with an invisible piece of dust. Microscopic grains in the disc grow by condensation, the same process behind snowflake formation. In condensation, individual heavy gas atoms or molecules stick to a grain, rapidly expanding its size into a more substantial solid particle.

When the particles are very small and light, turbulent gas motions stir them up, swirling them outside the flat plane of the proplyd. But when they reach sufficient mass they're heavy enough to settle into the

relatively thin rotating disc. In the crowded disc, particles collide more frequently, speeding up the growth of larger and larger chunks.

At about the point a chunk of solid matter grows to a kilometre across, it graduates to a planetesimal. A planetesimal is massive enough that its gravitational pull attracts smaller chunks of matter, accelerating the rate of growth. The result is a relatively small number of planetesimals steadily capturing the smaller chunks and particles in the disc.

When a terrestrial planetesimal grows large enough, the energy of many collisions along with radioactive material it's accreted heat everything to melting point. As a melted mass, the planetesimal's structure can reform. In a process called differentiation, the force of gravity concentrates the melted metals into an inner core, surrounded by an outer crust of lighter rocky silicates. The result is a protoplanet, an asteroid-like mass with distinct layers. Over time, gravity evens out the protoplanet's shape, forming it into a sphere.

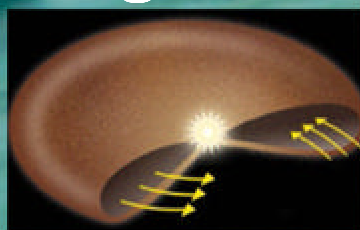
A terrestrial planet might form an atmosphere layer through outgassing. Essentially, heat from the planet's interior core unlocks gases trapped in the planet's solid and molten interior. Planets might then add to this atmosphere through encounters with other solar system bodies.

As the diversity of our own Solar System demonstrates, atmospheres vary a great deal. Any particular atmospheric recipe requires not only the right mix of planetary matter, but also a precise balance of planetary size and proximity to the central star. When a smaller planet orbits very close to a star, like Mercury, the sun's heat blasts away any atmosphere, leaving a barren rock. Meanwhile, a planet like Mars is so far from the Sun that all its water is locked up in ice. But just a bit further in, you get Earth – a planet that's the right size and in the right position to form a robust atmosphere that could support life.

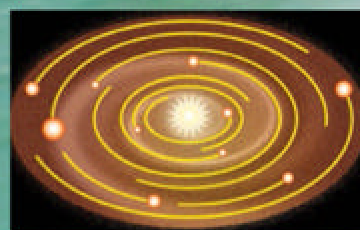
While there is general agreement among astronomers that terrestrial planets formed along these lines, the origins of Jovian gas giant planets, like Jupiter and Saturn, are less certain. One possibility is they start out the same basic way as terrestrial planets, steadily accreting solid matter to form a massive protoplanet. If it grows large enough – about 15 times the size of Earth – such a protoplanet exerts a strong enough gravitational pull to capture hydrogen and helium gas in

Origins of a solar system

Gas giant, the accretion model



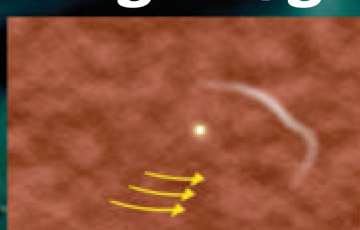
1. Dirty snowballs
Dust grains and bits of frozen hydrogen compounds condense and then collide and stick together, forming bigger and bigger icy planetesimals.



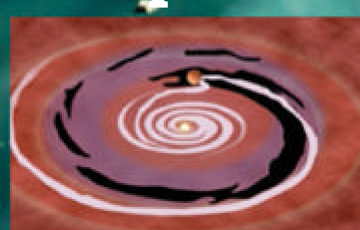
2. Capturing gas
Some planetesimals grow so big that their gravitational pull captures hydrogen and helium gas in the protoplanetary disc.

3. Too big to fail
The gas giants grab a huge supply of the disc's hydrogen and helium gas. Their massive gravity pulls in or scatters remaining planetesimals.

Gas giant, gas collapse model

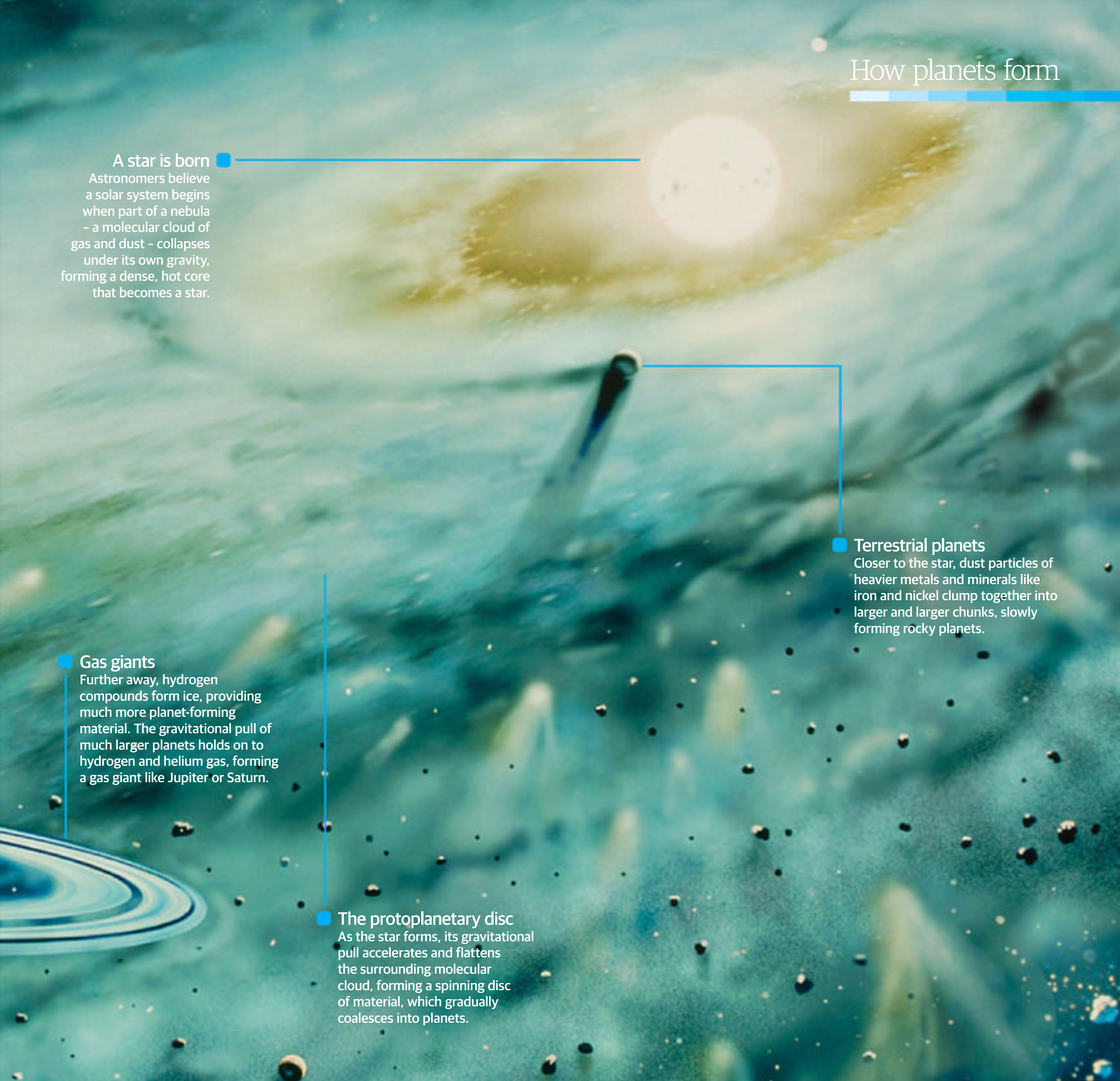


1. Concentrations in the disc
In the disc of gas and dust that forms around a protostar, the dynamics of the rotation cause uneven distribution of hydrogen and helium gas.



2. 'Instant' planet
A clump of dense gas collapses under its own gravity to form a gaseous planet. The new planet picks up dust and ice, which collect into a solid core.

3. Glutton for gas
As the planet makes its way around the disc, its strong gravitational pull sweeps up more gas, making it bigger and bigger.



A star is born
Astronomers believe a solar system begins when part of a nebula – a molecular cloud of gas and dust – collapses under its own gravity, forming a dense, hot core that becomes a star.

Terrestrial planets
Closer to the star, dust particles of heavier metals and minerals like iron and nickel clump together into larger and larger chunks, slowly forming rocky planets.

Gas giants
Further away, hydrogen compounds form ice, providing much more planet-forming material. The gravitational pull of much larger planets holds on to hydrogen and helium gas, forming a gas giant like Jupiter or Saturn.

The protoplanetary disc
As the star forms, its gravitational pull accelerates and flattens the surrounding molecular cloud, forming a spinning disc of material, which gradually coalesces into planets.

A terrestrial world is born

1. Let's stick together
Mineral and metal dust particles throughout the molecular cloud collide and clump together, forming larger rocky particles.

2. Running with the crowd
As trillions of these particles rotate around the developing star, they're constantly colliding, forming bigger asteroid-like pieces through accretion.

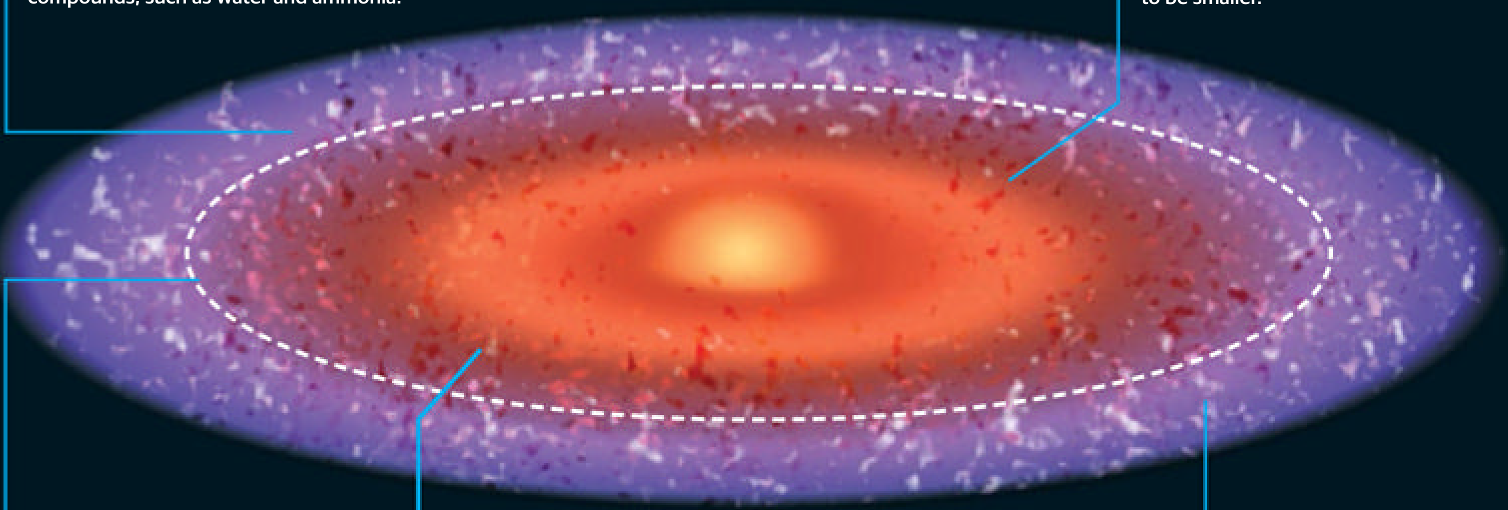
3. Forming a planetesimal
When a rocky chunk grows to about 1km across, its gravitational pull is able to attract other pieces, speeding up the accretion process.

4. Graduating to a protoplanet
Intense heat melts the rocky material. During melting, elements like iron and nickel concentrate at the centre of the planet, giving it distinct layers.

The frost line explained

Mainly gas
A protoplanetary disc is primarily made up of hydrogen, helium and various hydrogen compounds, such as water and ammonia.

Hot and rocky
Closer to the centre of a protoplanetary disc, the developing star makes it too hot for gases to freeze into a solid. Forming from a limited supply of metals and rocky material, inner planets tend to be smaller.



The frost line
The frost line marks the distance from the star where temperatures drop low enough for hydrogen compounds to freeze.

Hydrogen and helium gas
Hydrogen and helium gas exists throughout the protoplanetary disc, but temperatures never drop low enough for it to solidify. Only immense gravitational pull can condense it into a planet.

Icy planets
Beyond the frost line, gaseous hydrogen compounds like methane and ammonia condense into icy solids, which may form planetesimals.

the proplyd. The gaseous mass then sweeps up more material, growing into a Jovian behemoth.

There is a relatively small supply of heavy metals and silicate in a proplyd, making it unlikely that a protoplanet could accumulate enough metal and rocky material to reach the size necessary to hold on to hydrogen and helium gas. Instead, this model says, the initial planetary core of a Jovian planet forms out of frozen hydrogen compounds, such as methane, ammonia and water. Near the centre of a proplyd, the developing protostar makes it too hot for hydrogen compounds to condense into frozen solids. They remain in gaseous form and so do not accrete to developing planetesimals. But if you move far enough away from the hot protostar, past what's called the frost line, the temperature drops low enough that hydrogen compounds can freeze. With a much more abundant supply of solid material, large icy protoplanets can form and capture the swirling hydrogen and helium gas.

The organisation of our Solar System supports this theory. The inner planets, Mercury, Venus, Earth and Mars are all relatively small and rocky, suggesting forming giant icy or gaseous planets wasn't possible close to the Sun, while the outer planets, Jupiter, Saturn, Uranus and Neptune, are much larger.

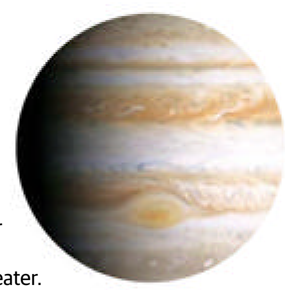
The chief argument against the accretion model for Jovian planets is timing. In well-supported models of solar system evolution, there simply isn't enough time to grow the massive icy cores before the developing solar system loses the bulk of its hydrogen and helium gas supply. While the lighter gases are the dominant material during the proplyd's early life, their days are numbered. In the case of our own Solar System, some 10 million years after the Sun first formed as a protostar, the energy of nuclear fusion reactions likely produced powerful solar winds that would have cleared out the remaining gas in the proplyd. That's a tight window for Jovian gas giants to form.

And neighbouring stars may lead to the window shrinking even further. Astronomers believe that stars generally form in clusters that contain massive, hot stars. Calculations say radiation from these stars would accelerate the evaporation of gaseous material in nearby proplyds, shrinking the period of plentiful hydrogen and helium to between 100,000 and 1 million years. That doesn't appear to be enough time for a Jovian gas giant

Types of planets

Terrestrial
Terrestrial planets like Earth and Mars are rocky planets with metal cores and high densities. They are smaller than gas giants and have slower rotation periods. In addition, their smaller size means they are less likely to have moons.

Gas giant
At a further distance from their orbiting star, gas giants are able to accrete more matter in their formation, giving them a large size and mass. For example, Jupiter is 11 times larger than Earth, and has a volume 1,300 times greater.

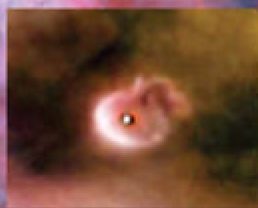


Dwarf planet
Smaller than a true planet, the difference between an asteroid and a dwarf planet comes down to its shape. To be a dwarf planet, a body must have sufficient mass to achieve hydrostatic equilibrium, when it will become spherical.

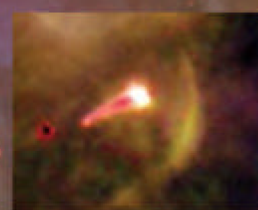
Planet formation in action

Our nearest star-forming region is the Orion Nebula, a massive cloud of gas and dust around 1,500 light years away. The striking nebula is visible to the naked eye - and positively breathtaking as seen through the Hubble Space Telescope. Hubble's sharp images, like this one from 2009, have revealed 42 protoplanetary discs (proplyds) where planet formation is now in progress. Theta^{1} Orionis C, the nebula's brightest star, heats nearby proplyds, giving them a bright glow. Proplyds forming further away are too dim to see, but their dark dust blocks out parts of the bright nebula in the background, creating silhouettes astronomers can study.

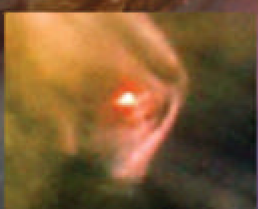
132-1832
Developing far from Theta^{1} Orionis C, 132-1832 is one of the darker proplyds in the nebula.



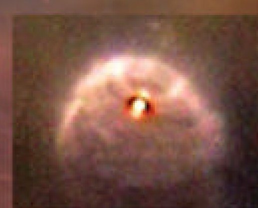
206-446
Astronomers believe this bright proplyd's distinctive ponytail-style plume is a jet of matter streaming out from the disc's centre.



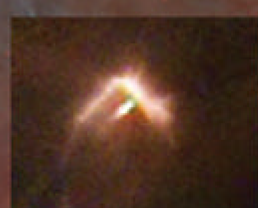
180-331
Proplyd 180-331, another bright disc near Theta^{1} Orionis C, also sports a flowing jet of matter, giving it a tadpole shape.



106-417
Stellar wind from the massive Theta 1 Orionis C interacting with gas has formed a shockwave around this ear-shaped proplyd.



181-825
But the best shockwave sculpture has to be 181-825's distinctive galactic jellyfish form.



231-838
Like 106-417, the bright proplyd 231-838 is surrounded by a shockwave, giving it a boomerang shape.

> "The origins of Jovian gas giant planets, like Jupiter and Saturn, are less certain"

to form through the accretion model, yet observations of distant solar systems show that these gas giants are very common.

An alternative theory, known as the gas collapse model, presents a faster formation scenario. According to this model, gas giants form directly from the swirling hydrogen and helium in a developing proplyd. As the material revolves around the protostar, turbulence in the disc distributes it unevenly. This unevenness forms knots of dense gas. When enough gas is concentrated tightly enough, its dense mass causes it to collapse in on itself, forming a giant gas ball. To put it another way, the gas giant is like a failed star. It forms the same basic way as the protostar, but doesn't have sufficient mass and energy for a nuclear fusion reaction.

The embryonic planet's gravitational pull takes over from there, sweeping up massive amounts of gas, as well as any solids in the vicinity, quickly adding to its bulk. Collected ice and metals condense at the planet's centre, forming a solid core after the gas has accumulated, rather than before. The whole process might happen as quickly as a few hundred years.

Observations of Jovian exoplanets (planets located outside our Solar System) have given some credence to this model - or at least challenged the Jovian accretion model. In the wave of exoplanet discoveries over the past 25 years, one of the biggest surprises has been the so-called 'hot Jupiters', Jovian gas giants that orbit very close to their suns. These planets would seem to contradict the notion that gas giants only form beyond the frost line. However, they may have formed further out, but then migrated towards their suns.

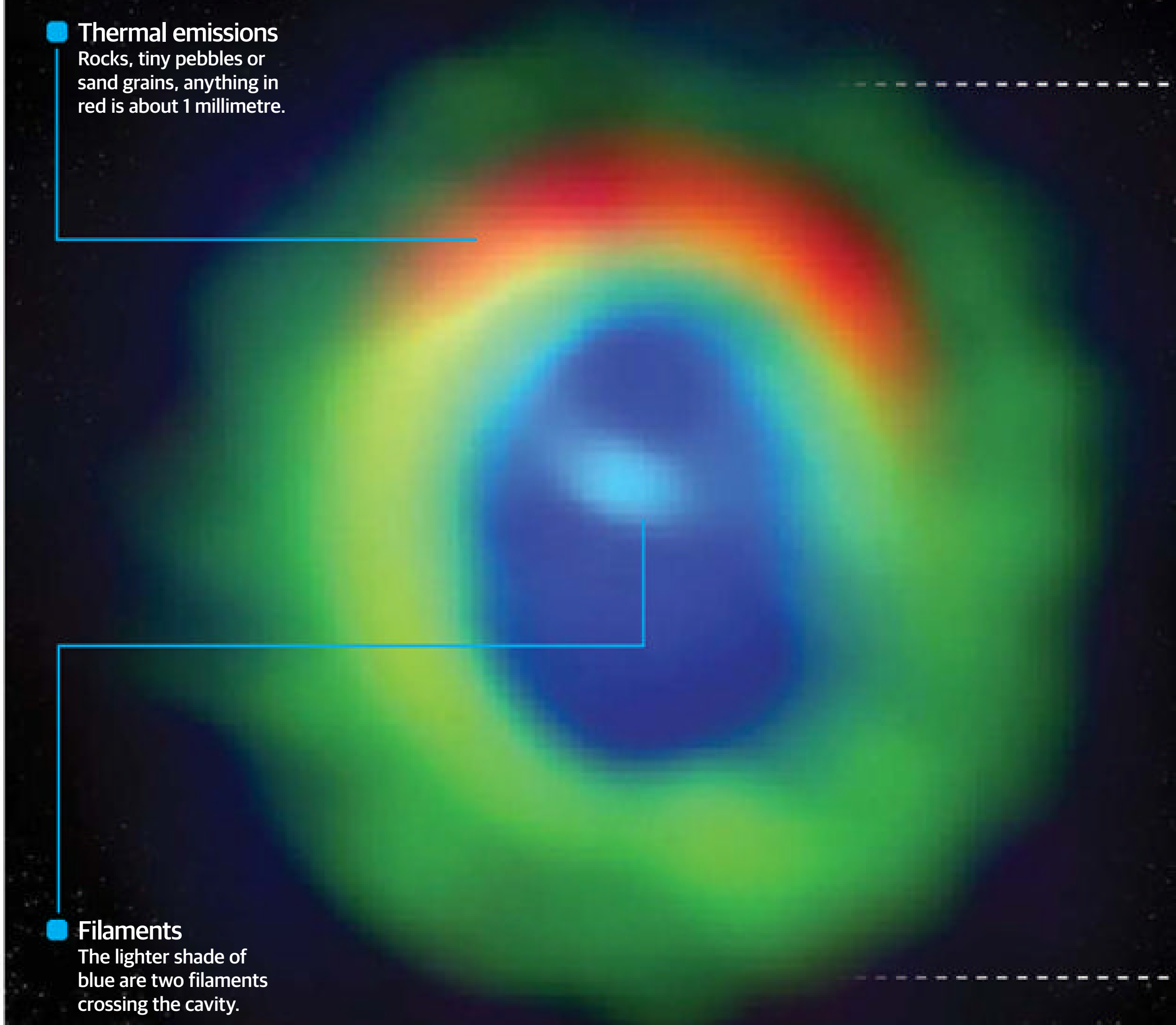
A host of exoplanet discoveries have given astronomers a better picture of the range of possible planets, which has yielded new clues about how planets form. But examining the end results can only tell them so much. Fortunately, we're likely entering a new era of direct proplyd observation, thanks to advances in telescopic technology. The new Atacama Large Millimeter/submillimeter Array (ALMA) radio telescope in Chile, which should be fully operational in March, has already yielded unprecedented images of planet formation in progress. As new discoveries follow, astronomers expect to fill in more pieces of the puzzle, taking us ever closer to understanding how our planet, and by extension all of us, came to be. ●

Discovering a protoplanet

Dr Simon Casassus of the University of Chile talks us through fascinating images of a protoplanetary disc in action more than 450 light years away

In January, the University of Chile published images showing a protoplanetary disc in action around HD 142527, a young star over 450 light years away. Can you describe the data shown in the image?
This is a protoplanetary system seen face-on. In red is the thermal emission from rocks or tiny pebbles or sand grains. The size of these particles is about one millimetre. The rest of the colours are gaseous. In green, we see the Formyl ion molecule and in blue we have carbon monoxide. In a lighter blue, there are two filaments crossing the cavity that converge on the centre where the star would be. Those filaments are faint compared to the rest of the nebula, but they are there. This is the first time we've seen such cavity-crossing flows. The other first is the (darker) blue, the diffused carbon monoxide, which is slightly less dense material, more rarified gas.

We think that (gas) giants have formed first through a rocky core… a super-Earth exoplanet, something like ten times the mass of the Earth, which is massive enough to attract and hold the gas in the disc, so it



sucks away a cavity, which goes into the body of the planet. So the planet grows at the expense of the disc and clears away a cavity. The size of the cavity we see in this system suggests it's been carved out by several planets. This is what the hydro-simulations tell us. The race is on to detect those protoplanets and confirm the theory.

The planet is growing and at the same time clearing away this cavity. The way it manages to keep on growing is by sucking material from the outer regions. This material falls on to the star and crosses the planets as they fall, because they're being perturbed by the gravitational interference from the planets. They catch some of the falling material. But the rest of it just overshoots and reaches the inner disc, which is the other side of the cavity. The rate of inflow of material here is right to sustain the continuous growth.

Does this reflect something that happens in most cases of planet formation or is this a special case?

We don't know. Before we can extrapolate to other planetary systems, and before we can conclude that for sure the early Solar System looked like this, we have to find some other examples.

This is the first time we have seen these radial flows and this residual gas inside a planetary cavity, and we detected the features at the limit of the capabilities for ALMA in its first year of operations. So we now need to study it in more detail and collect similar data around other young stars.

Was there any data in your findings that challenged existing models of planet formation?

That's a hard question because there are so many different models of planet formation. But there are some versions of planet formation which predict very late formation of planets, slower than tens of millions of years, and this one is about two million years.

> "This is the first time we have seen these radial flows inside a planetary cavity"

Is it possible that our own Solar System followed a similar sequence of events?

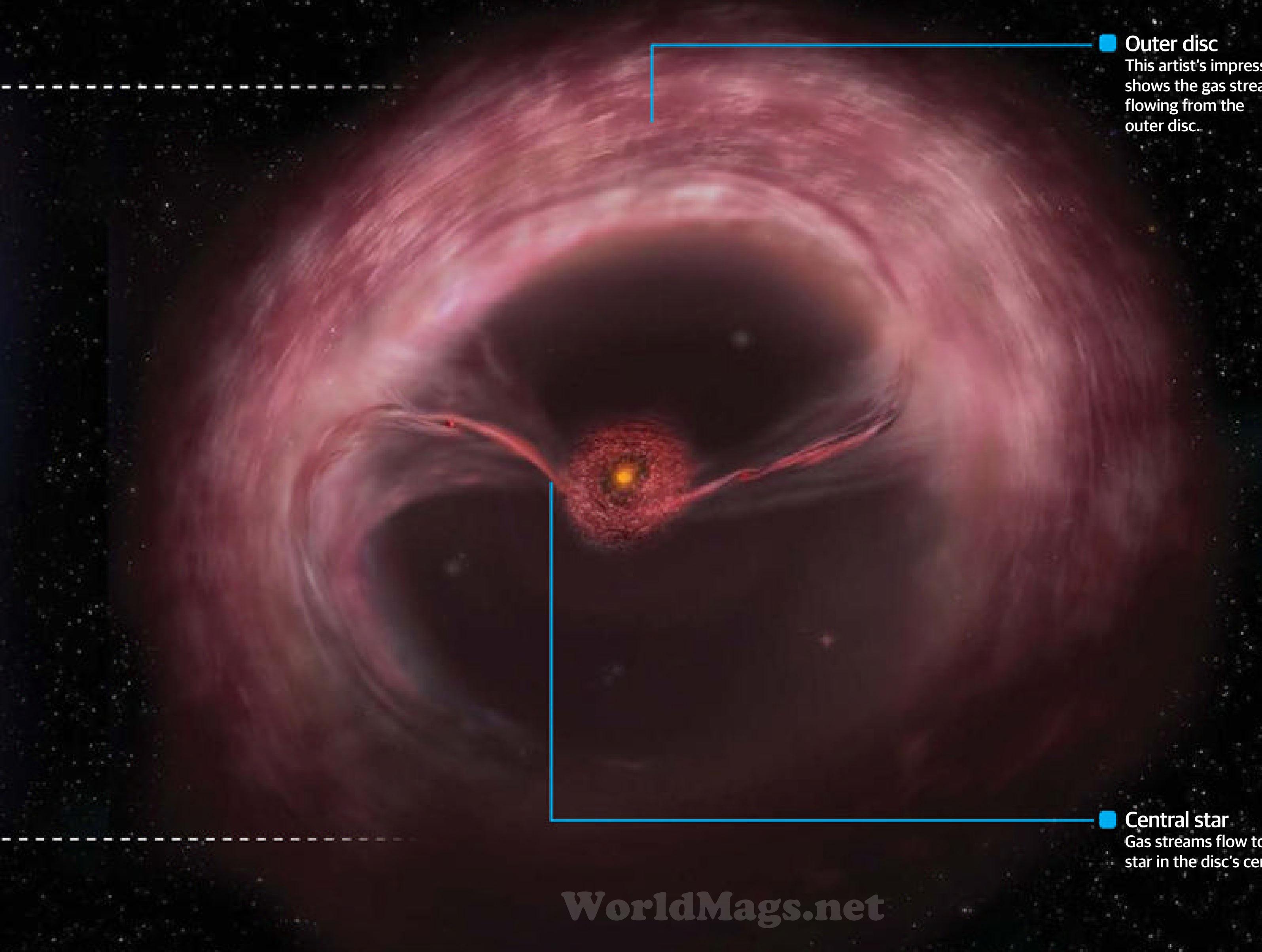
Could be. That's what's so astonishing. If you consider this nebula, it's a protoplanetary disc around the star called HD 142527. In this system the protoplanets are formed really far out from the star. Our hydro-simulations tell us that the protoplanets form around 100AU from the star, whereas Jupiter is at 5AU [from our Sun]. So, is this system comparable to our Solar System? At first, you would say, no, because it's so much bigger. But you also have to think about planet migration. Newborn planets migrate. It is possible for a gaseous giant to migrate from the outer regions at 100AU down to 5AU.

Are there other theoretical phenomena that you're looking to see in future observations?

Yes. There are proto-lunar discs, the circumplanetary discs, which we hope to detect. This would be a way to pinpoint the location of protoplanets.

What's next for your team?

We are still analysing this data. Then I'm expecting the rest of the ALMA data and complementary infrared observations. We applied a variety of techniques in the hope of detecting the protoplanets.



Outer disc
This artist's impression shows the gas streams flowing from the outer disc.

Central star
Gas streams flow to the star in the disc's centre.

Creating a GALAXY

The making of these billion-star structures has been puzzling astronomers for decades. We put together the pieces for building a galaxy

The universe is packed with galaxies. Everywhere we look and at almost every point in history we see galaxies crammed into the cosmos, grouped in clusters and great sheets that criss-cross through space-time. The most distant galaxies ever seen have been identified by the Hubble Space Telescope as being 13.2 billion light years away. Yet these are not even the most distant galactic structures out there. It's the first galaxies that hold the record for being the furthest away from us. However, we're yet to see them. To do so we will need the infrared prowess of the James Webb Space Telescope (JWST), which will be able to see galaxies as they are forming just 300 or 400 million years after the Big Bang – the event that threw the cosmos into existence.

Understanding how galaxies form is a bit like trying to put a jigsaw together. Think of each galaxy

as being a piece of that puzzle. Because galaxies are so old and evolve so slowly, when we see a galaxy in the night sky we are just seeing a single snapshot of their long lives. However, the galaxies are all at different stages of their evolution, so if we can put all these snapshots together, like the pieces of a puzzle, we can build an overall picture of how galaxies like our own Milky Way grew into the star, dust, gas and dark matter packed structures we see today.

We've actually only known that there are galaxies in the universe beyond our own Milky Way for less than a hundred years. Before that time astronomers thought that the weird objects they dubbed 'spiral nebulae' were actually part of our galaxy. Their telescopes were not powerful enough to resolve individual stars in these objects, although when astronomers looked at the light coming from them, they had all of the evidence they needed to confirm that these blobs in the night sky were made up of many stars. In 1912, American astronomer Vesto Slipher found that the very light being thrown out by the spirals was Doppler shifted toward redder wavelengths, meaning the spiral nebulae are moving away from us and take on a red tint.

Doppler shift is the compression or stretching of light waves as an object moves toward or away from us. You might not have realised it, but you have experienced a Doppler shift before since it also happens with sound waves. When a police car or ambulance has raced past you with its siren blaring, the pitch of the sound it makes changes depending on its distance. At first it is higher and then becomes lower as it moves away since the sound waves become compressed and then stretched.

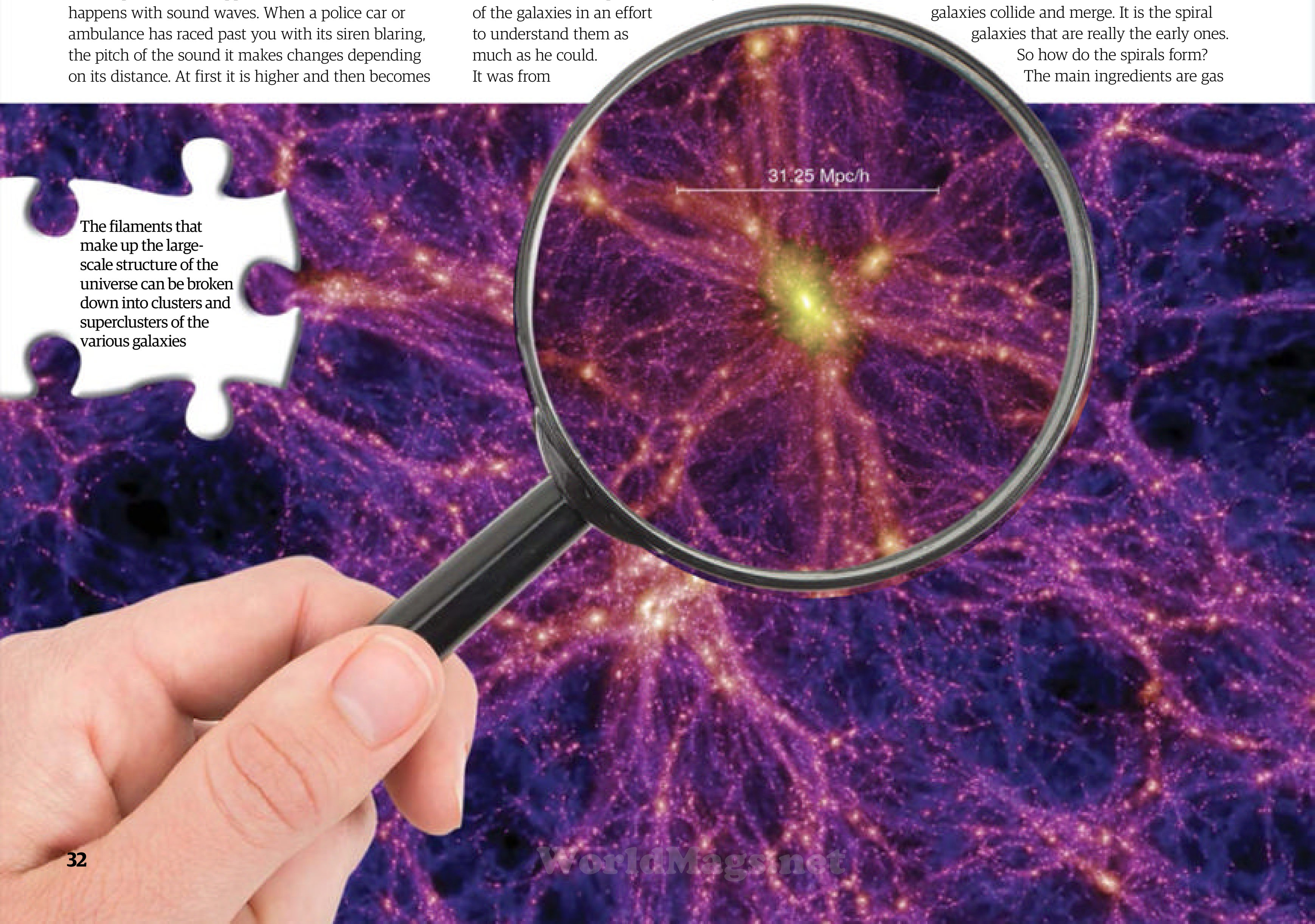
In 1925, Edwin Hubble announced he had discovered that the spiral nebulae were all galaxies, or island universes far beyond our own. He achieved this thanks to the biggest telescope in the world at the time, the 2.5-metre (8.2-foot) mirrored Hooker Telescope at Mount Wilson in California. Hubble was able to resolve individual stars, including a specific type called a Cepheid Variable. This type of star throws out light, which varies according to its true brightness and from this observation astronomers can work out their distance. It was the Cepheids found in our neighbouring galaxy of Andromeda that allowed astronomers to measure the distance to our closest spiral as 2.5 million light years away. Coupled with Vesto Slipher's discovery that the galaxies are all moving away from us, scientists quickly realised that once upon a time they must have been much closer together than previously anticipated.

Hubble's next step was to classify all of the galaxies in an effort to understand them as much as he could. It was from this that he created his famous tuning fork diagram. He built his diagram so that its handle is made up of elliptical galaxies, which are galactic structures with ovoid shapes. Hubble referred to these as early-type galaxies because he believed that all galaxies began their lives as ellipticals before evolving into one of two types of spiral galaxy, which formed the prongs of his tuning fork. One type are the regular grand design galaxies with their graceful spiral arms curving away from a small central bulge, while the second type are the barred spirals, whose spiral arms are connected with a long, straight bar running through their glowing centres. In fact, today it's believed that our very own galaxy has a bar running through its centre.

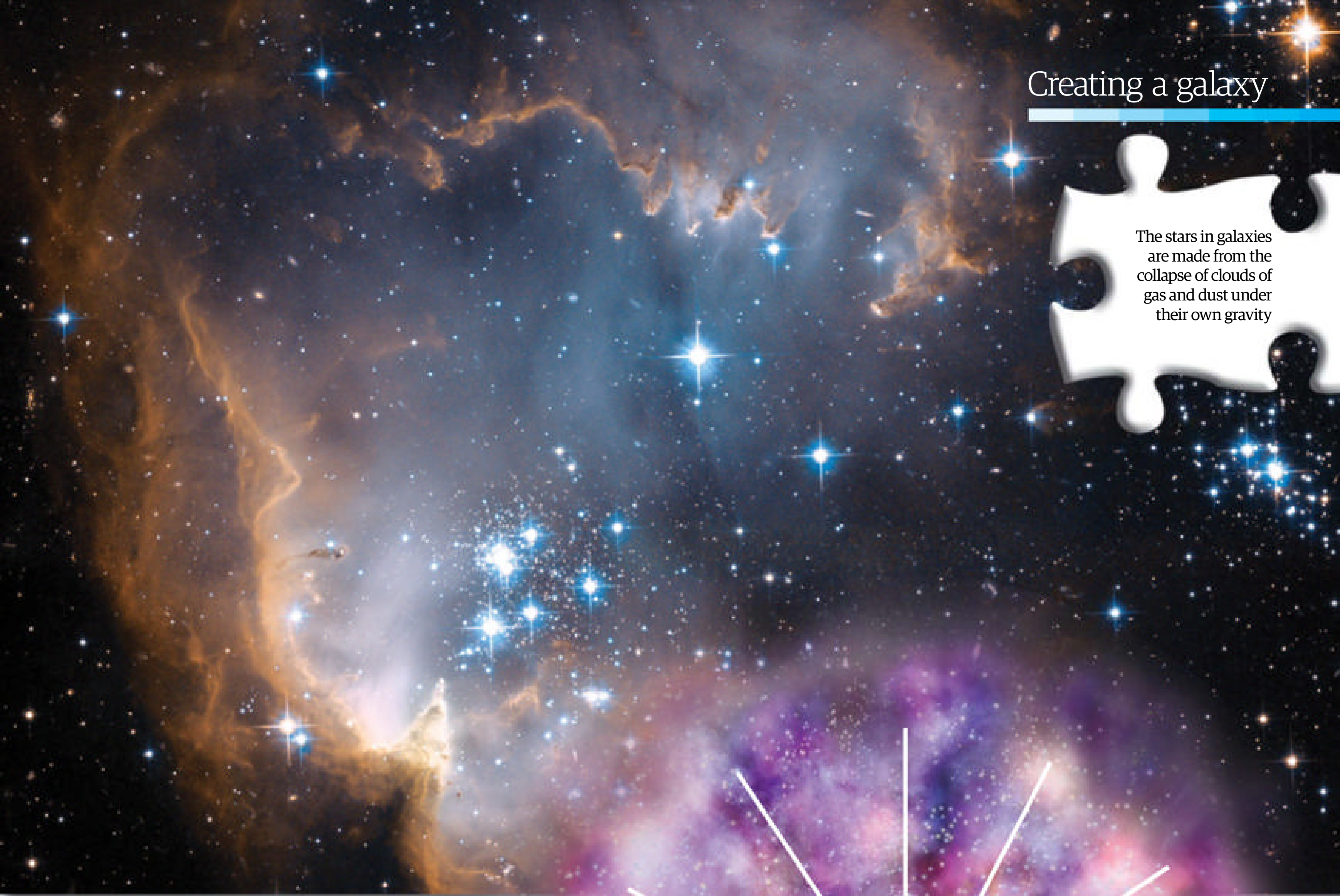
> "He built his diagram so that its handle is made up of elliptical galaxies... which formed the prongs of his tuning fork"

Hubble thought that the elliptical galaxies were the bulges of spiral galaxies but without the arms, which he assumed grew later. Aastronomers changed their minds about this after studying galaxies in more detail throughout the 20th century. They found that elliptical galaxies form when two or more spiral galaxies collide and merge. It is the spiral galaxies that are really the early ones.

So how do the spirals form? The main ingredients are gas



The filaments that make up the large-scale structure of the universe can be broken down into clusters and superclusters of the various galaxies



The stars in galaxies are made from the collapse of clouds of gas and dust under their own gravity

(predominantly hydrogen) and that mysterious substance called dark matter. Nobody knows what dark matter is, but we know it comes in the shape of giant blobs scattered throughout the universe. Some of these dark matter blobs are large enough to hold clusters of thousands of galaxies. The dark matter came first, forming these blobs, or haloes, very soon after the Big Bang. The gravity of these haloes began to attract hydrogen gas toward them, which began to flow like rivers along gravitational inclines created by the influence of dark matter into the cores of the blobs. There the hydrogen formed enormous spinning clouds and the hydrogen and dark matter formed the embryo of a galaxy. Think of the white and the yolk of an egg as the dark matter with the hydrogen at the core.

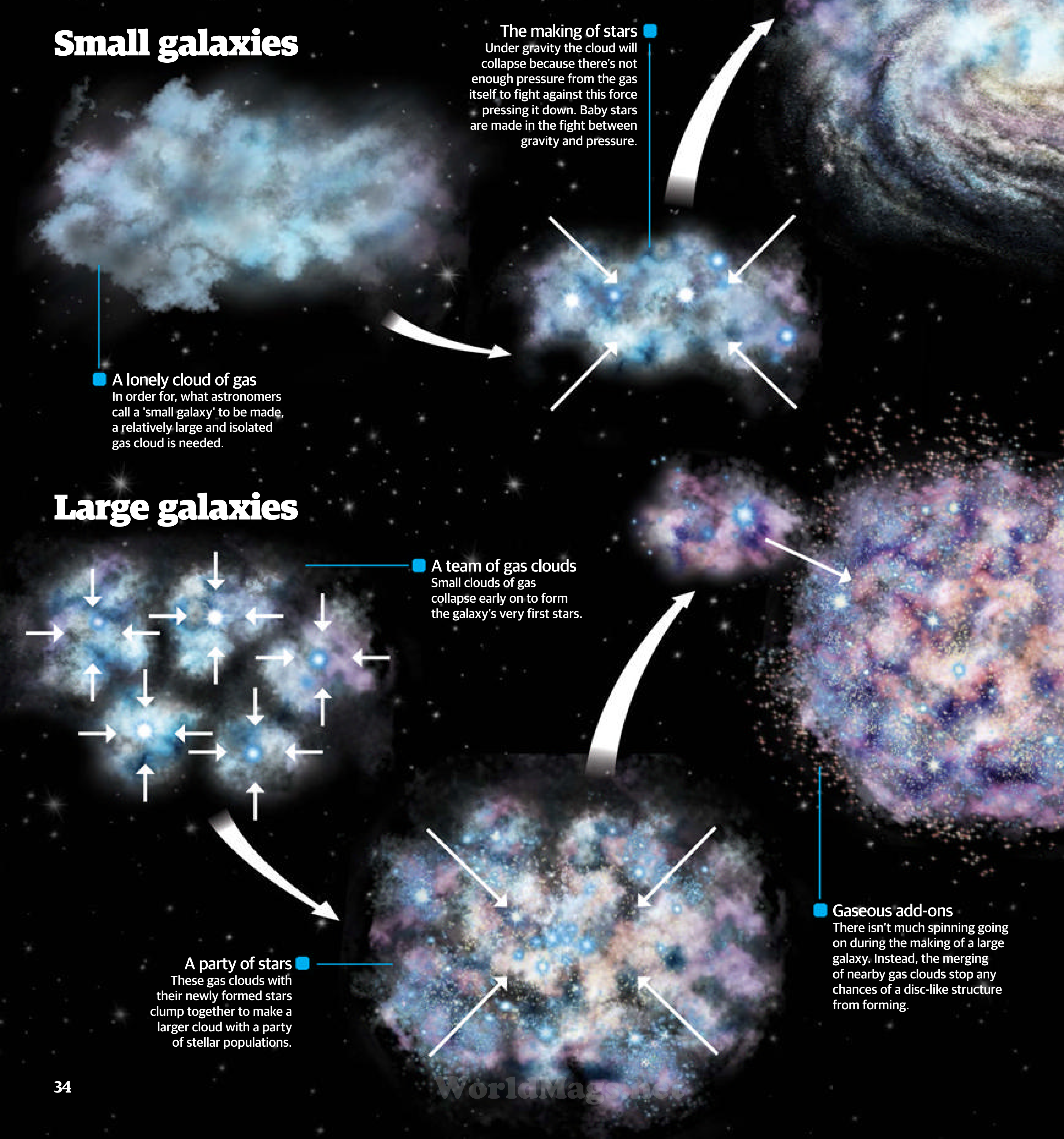
Because the dark matter and hydrogen mixture was spinning so fast, it flattened into a pancake shape, taking on the characteristics of a spiral galaxy's flat disc. Meanwhile, small pockets of hydrogen gas in the cloud collapsed to form the very first stars. These stars were gigantic, hundreds of times more massive than our relatively puny Sun and they exploded very quickly as powerful supernovae. Stars are able to create elements in their cores, while the violence of exploding stars, known as supernovae, can form even more new elements. When the first stars detonated, they spilled their guts into the baby galaxy around them, enriching it with these heavy elements. Over time, enough of these elements would build up to form asteroids, moons and planets. When we look at galaxies today, including our own Milky Way, we see vast lanes of

It's thought that galaxies are made from the collapse of protogalactic clouds of dense hydrogen and helium gas in the early universe

"The black hole in the centre of the Milky Way galaxy is four million-times more massive than the Sun"

Galactic evolution

How their different sizes can affect how galaxies form



Small galaxies

A lonely cloud of gas

In order for, what astronomers call a 'small galaxy' to be made, a relatively large and isolated gas cloud is needed.

The making of stars

Under gravity the cloud will collapse because there's not enough pressure from the gas itself to fight against this force pressing it down. Baby stars are made in the fight between gravity and pressure.

Large galaxies

A team of gas clouds

Small clouds of gas collapse early on to form the galaxy's very first stars.

A party of stars

These gas clouds with their newly formed stars clump together to make a larger cloud with a party of stellar populations.

Gaseous add-ons

There isn't much spinning going on during the making of a large galaxy. Instead, the merging of nearby gas clouds stop any chances of a disc-like structure from forming.

black dust. This dust is comprised of elements made inside the nuclear furnaces of stars, dating back to the first stars that existed about 13.5 billion years ago.

Today we find that the oldest parts of spiral galaxies are their bulges. In these central regions most of the gas has been used up and the stars that exist there are crammed together and more red than the combined light of the stars in the spiral arms, which are dominated by hot, young stars. The exception is in the few tens of light years immediately around the supermassive black hole that lies in the middle of every large galaxy, where the gas is dense enough to keep forming new star clusters made of massive stars.

The black holes in the centres of galaxies are enormous. The black hole in the centre of the Milky Way galaxy is four million-times more massive than the Sun. In other galaxies, black holes can be tens or even hundreds of millions of times more massive. The biggest galaxies of all, the giant ellipticals found in the centres of galaxy clusters, have central black holes with masses up to a billion-times that of the Sun, as is the case with the galaxy M87 in the heart of the Virgo galaxy cluster.

Everyone knows that black holes like to consume matter, that's how they grow so big. But black holes can't eat everything that is served their way and sometimes they spit out their food. What happens is that as gas flows toward a black hole, it whirls around into a disc of material spiralling into the it. However, the gas brings magnetic fields with it that become wrapped up around the black hole by the swirling gas. Eventually the magnetic fields become so strong that they can actually begin to funnel away charged particles, atoms, protons, electrons and ions into jets that are so energised they race away from the black hole at almost the speed of light. We can even see one of the jets coming from the black hole in M87.

The level of black hole activity can depend on many factors, such as the mass of the black hole and the amount of gas falling into it. Our Milky Way's supermassive black hole, for instance, is very quiet with hardly any gas falling into it. Other spiral galaxies have more activity in their centres, with some emitting strong radio waves. However, the most active black holes are called quasars. The closest to us is 2.4 billion light years away, but the majority existed in the universe over 10 billion years ago.

Quasars are fed by gas in two different ways: one is simply clouds of intergalactic gas falling onto a black hole in the centre of a galaxy. These clouds are clumps of gas and dark matter left over from the process of building galaxies over 13 billion years ago. The other way that quasars light up is more exciting, when two galaxies come hurtling toward each other and collide, it causes huge clouds of interstellar gas and stars to fall into the black hole.

Sometimes the collision is a hit and run. The gravitational forces of each galaxy tear stars and gas out into long streamers that astronomers call tidal streams. These streams can sometimes be many hundreds of thousands of light years long.

When galaxies collide it changes the future of the structures involved. Going back in time by 13 billion years, Hubble is able to see the first galaxies growing by consuming smaller galaxies. This galactic cannibalism continues even today, although at a

Lighthouse of the cosmos

Quasars blaze radiation that can be seen from the other side of space

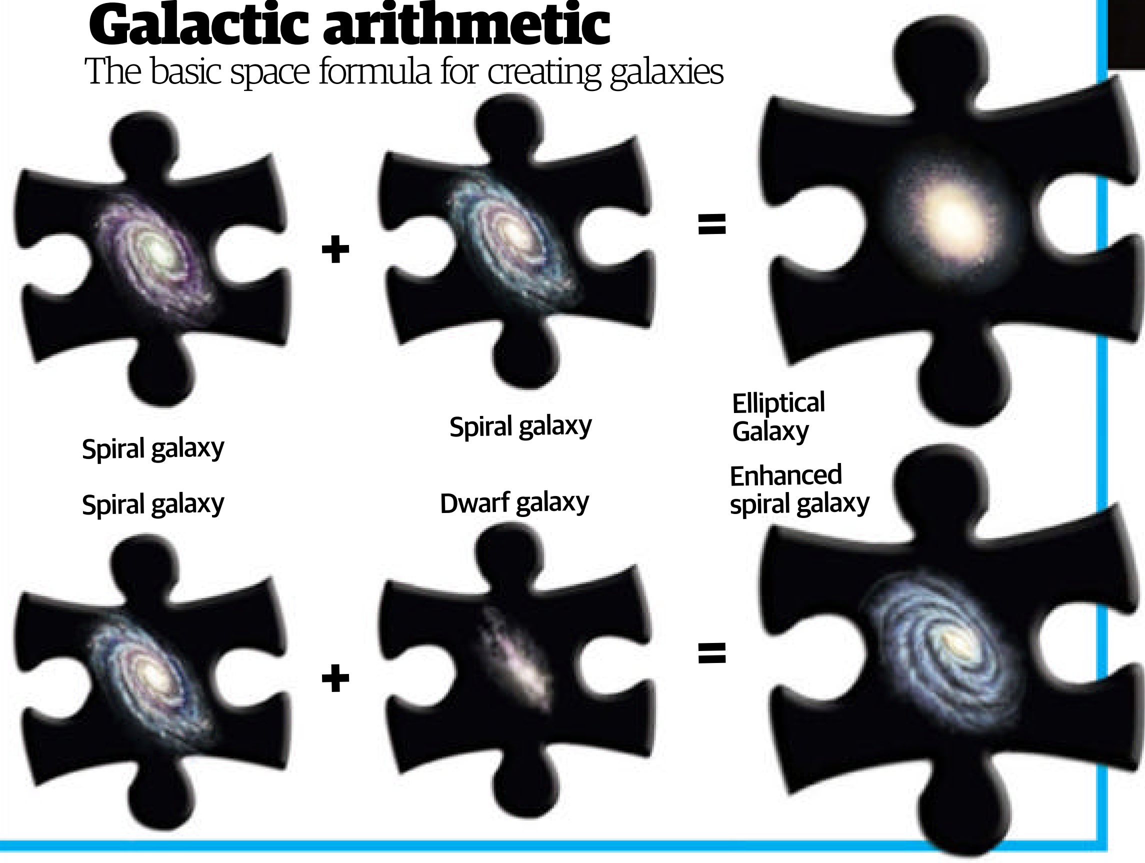
The 'calm' black hole
If a black hole is calmly sitting at the centre of its galaxy, it generally distorts the fabric of the universe around it. It leaves a dent in this sheet of space-time from which nothing – not even light – can escape.

A swirling disc of dust and gas
An accretion disc made of gas and dust circles the black hole. If the black hole isn't particularly active, then the matter won't fall into it.

Heating up
When the material falls into the black hole and reaches the event horizon – the point of no return – a lot of friction is created, superheating atoms and tearing them apart.

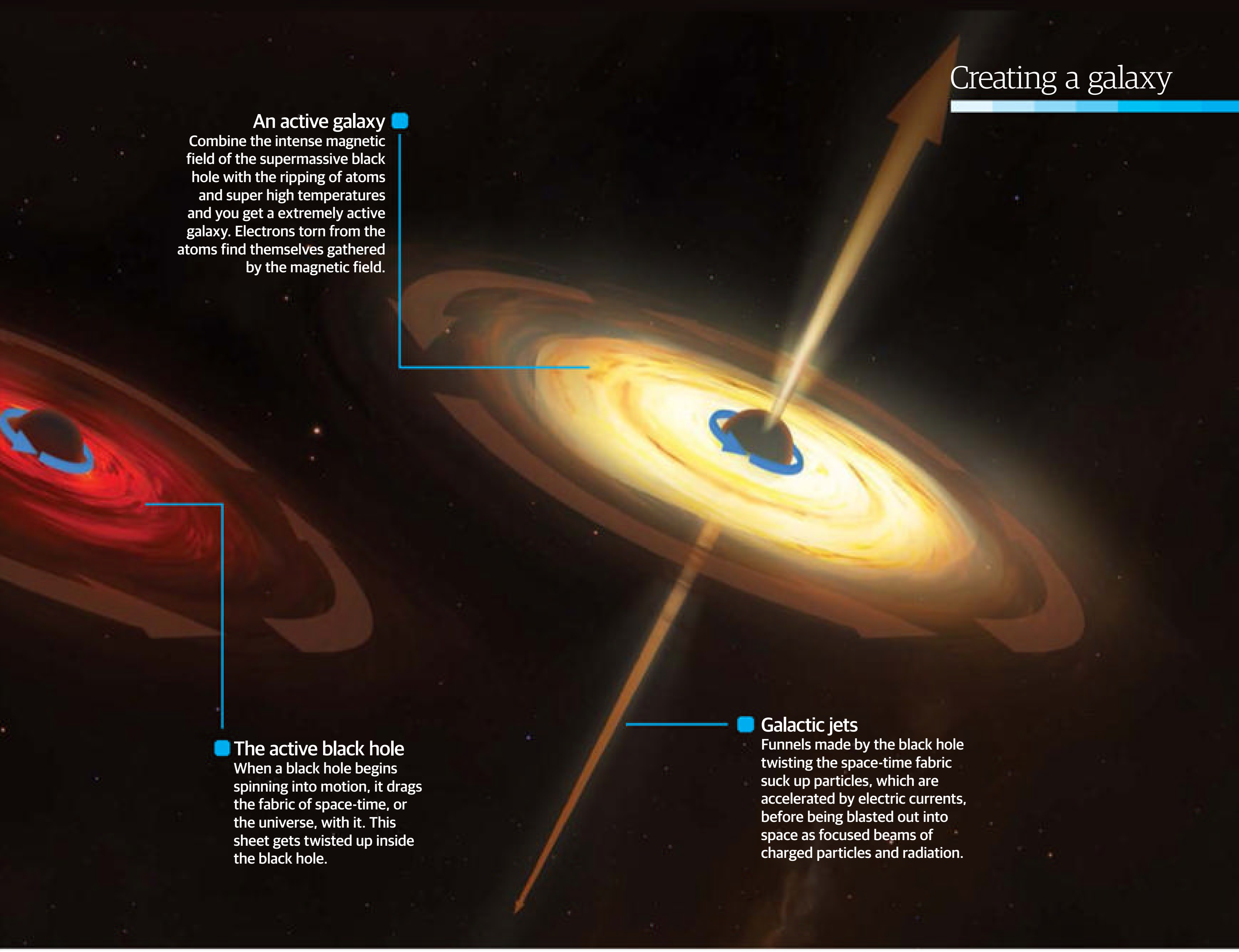
Galactic arithmetic

The basic space formula for creating galaxies



much slower rate. Even the Milky Way is eating smaller galaxies at this very moment but they are not going near our black hole, so the centre of our galaxy is not active. For example, the Canis Major dwarf galaxy is only 25,000 light years from Earth and is merging with our galaxy. It contains few stars because the gravity of the Milky Way has stripped most of them away.

Astronomers call such collisions minor mergers and the end result is that the smaller galaxy is swallowed up, increasing the mass of the larger galaxy. At the other end of the scale are the major mergers, between two large galaxies of around the same size. When two spiral galaxies collide like this, it destroys their spiral structures and they merge into a giant elliptical galaxy – the opposite of what Hubble's tuning fork suggests. Amazingly, during a galaxy collision no stars actually collide, because the space between the stars is so large that the chances of two stars coming within each other's gravitational sphere of influence is very small. That means that when our Milky Way galaxy undergoes the next phase of its growth and merges with the Andromeda galaxy in 4 or 5 billion years, our Sun will not collide with another star from Andromeda. What will collide will be the huge clouds of interstellar gas that inhabit the spiral arms of both galaxies, igniting in a huge

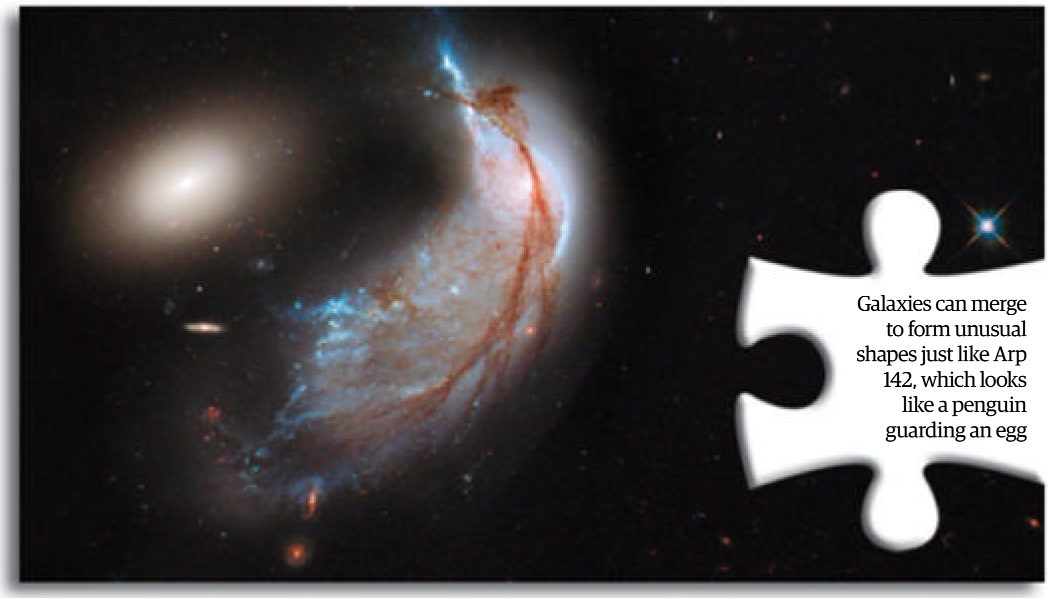


burst of star formation. We call this a starburst and they can use up all the gas in a galaxy. This is why most elliptical galaxies, which form from mergers, have no star forming gas left and haven't made any new stars in a very long time. All their short-lived, young stars exploded long ago, leaving ellipticals dusty and red with older, cool stars.

No galaxies are being made today. All that galactic construction happened over 13 billion years ago and ever since it has been a case of galactic evolution rather than galactic formation. There are still some crucial pieces of the jigsaw missing, such as whether supermassive black holes formed before the galaxies that exist around them or vice versa, why the disc turns into spiral arms and why these arms do not wind up as they rotate around the centre of the galaxy. Some scientists think that the spiral arms are not actually rigid appendages, but density waves where stars and gas are bunching up. This is a bit like a traffic jam on a motorway and as soon as some stars hit the brakes and slow down all the other stars and gas clouds bunch up behind them.

Although some of the pieces are missing, the jigsaw of how galaxies are made, grow and evolve is becoming clearer. We might not be able to see everything, but we can see enough to understand when and where galaxies came from.

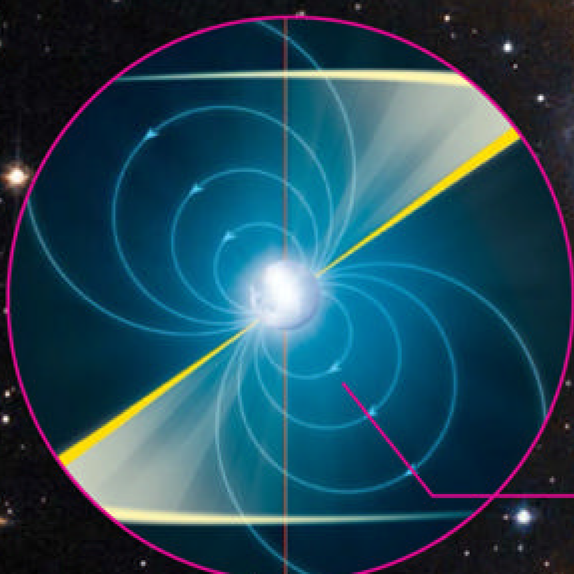
"When two spiral galaxies collide, it destroys their spiral structures and they merge into a giant elliptical"



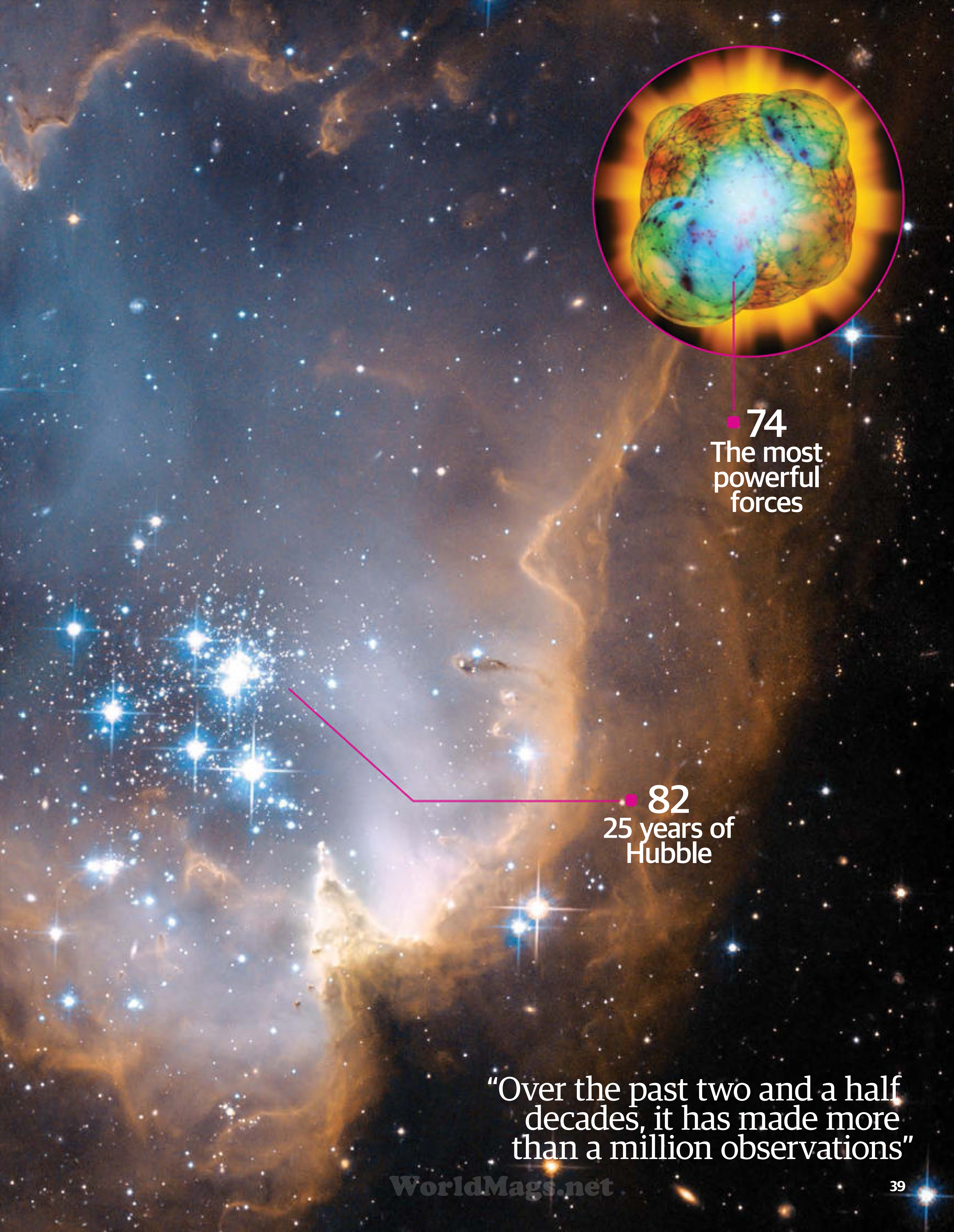
Galaxies can merge to form unusual shapes just like Arp 142, which looks like a penguin guarding an egg

Secrets of the universe

Uncover the most intriguing aspects of our universe



40
100 wonders of space



74
The most powerful forces

82
25 years of Hubble

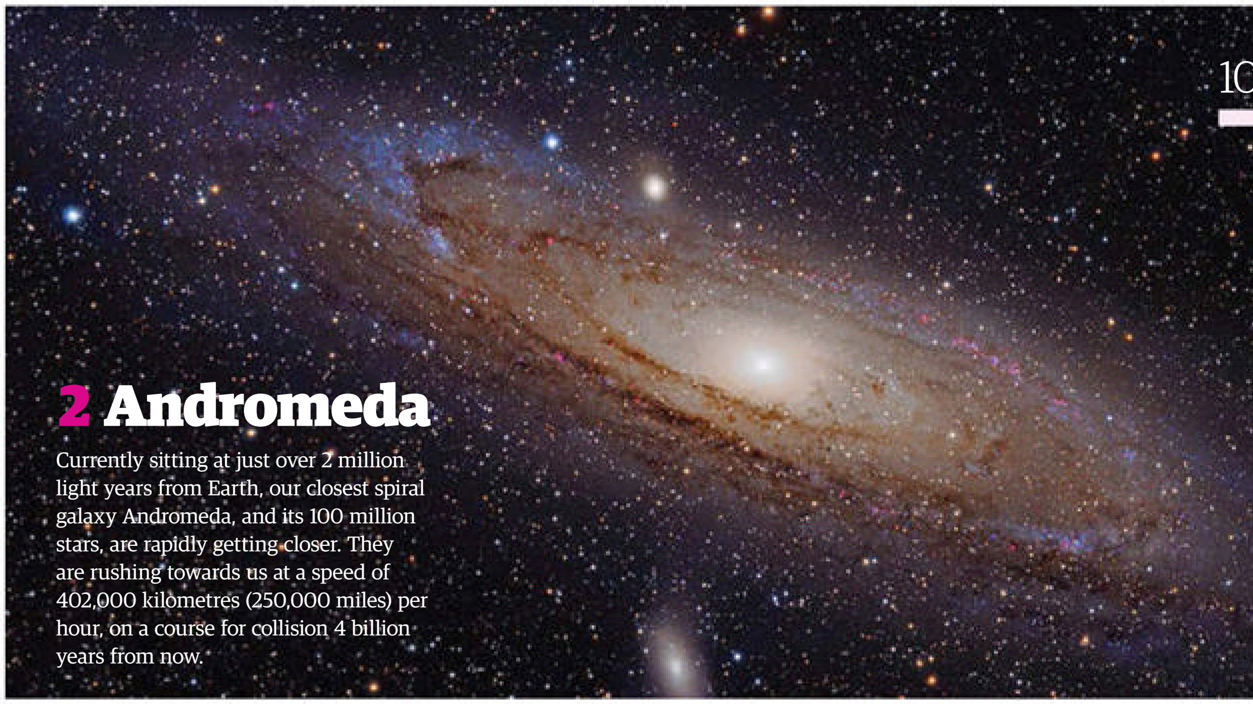
"Over the past two and a half decades, it has made more than a million observations"

100 wonders of space

From giant craters to supermassive black holes and alien planets: explore our favourite parts of the cosmos

1 Saturn's Rings

The rings of Saturn are extraordinary. First observed by Galileo Galilei in 1610, these structures are incredibly thin, measuring just one kilometre (0.62 miles) from top to bottom. They're made up of billions of particles of ice and rock, some as large as mountains and others too small to be seen with the naked eye. It's not known for sure how old the rings are, or exactly how they formed, but it is thought possible that the fragments are pieces of shattered moons, smashed to bits by collisions in the not too distant past.

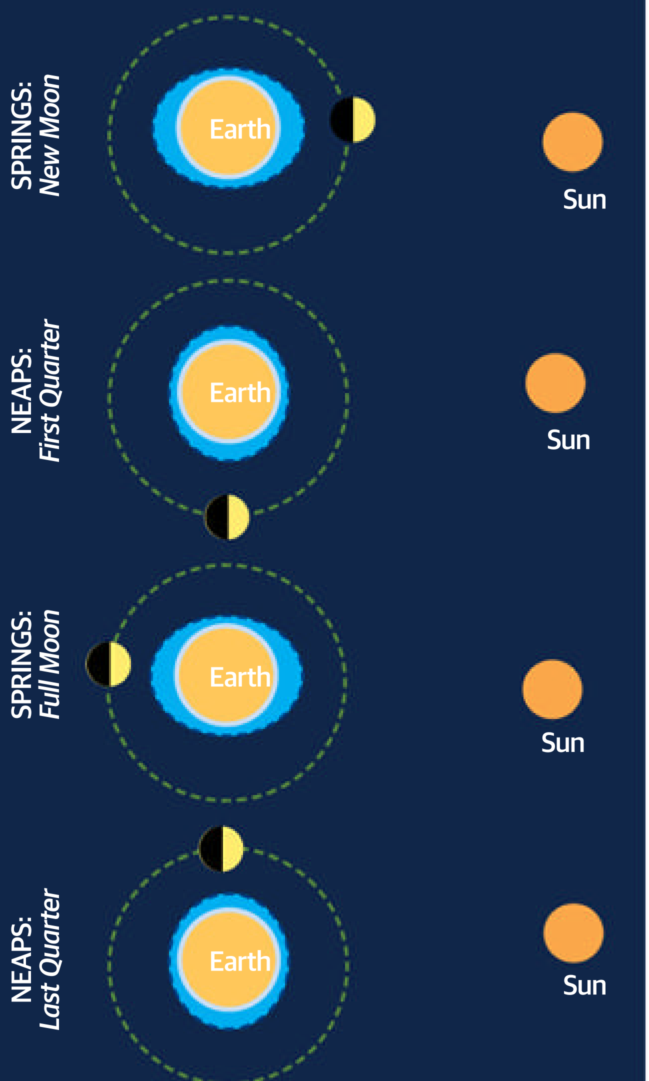


2 Andromeda

Currently sitting at just over 2 million light years from Earth, our closest spiral galaxy Andromeda, and its 100 million stars, are rapidly getting closer. They are rushing towards us at a speed of 402,000 kilometres (250,000 miles) per hour, on a course for collision 4 billion years from now.

3 The Moon

The Moon is a space wonder right on our own doorstep. As it orbits the Earth, its gravity tugs on the oceans, creating a measurable bulge; as the oceans swell, we see the effects on the ground as tides. The Sun has a similar, but smaller, effect, and when the Moon and the Sun are in line, the pull on the oceans adds together, creating extra high 'spring tides' once a fortnight.



4 The Pillars of Creation

These iconic columns of gas and dust were first imaged by the Hubble Space Telescope in 1995, and in 2015 the pictures were retaken in high definition. Lit by ultraviolet radiation released by massive, young stars in the Eagle Nebula, the pillars are constantly being shaped, heated and eroded, and hidden inside are the infrared traces of brand-new stars.

5 Sombrero Galaxy

Named for its hat-like appearance, the Sombrero is a galaxy within a galaxy. The flat disc, viewed almost side-on from the Earth is the most obvious feature, resembling the wide brim of a hat, but if you look again in the infrared spectrum a much larger elliptical galaxy becomes visible, completely encasing the central disc.

6 Life

As far as we know, Earth is the only planet to harbour living organisms, but chances are there are many more planets out there like our own.

7 Great Red Spot

The width of two Earths, Jupiter's Red Spot is by far the biggest storm in the Solar System, and is given its red colour by the effects of UV light on the clouds.

8 Leonids meteor shower

These meteors shower the atmosphere every November as we pass through a trail of dust and gas left by comet Tempel-Tuttle as it nears the Sun.

9 Methane seas

Weather is not exclusive to water worlds like our own; Saturn's moon Titan has seas, clouds and rain of liquid methane.

10 Giant moon cliff

The tallest cliff in the Solar System is on Uranus's moon, Miranda. Verona Rupes is 20 kilometres (12 miles) deep, and it would take 12 minutes to fall from top to bottom.

11 Acid atmosphere

The atmosphere of Venus is 96 per cent carbon dioxide, and the pressure at the surface is 90 times that on Earth. It has little water, and the clouds are made from corrosive sulphuric acid.

12 Accretion disc

Black holes are surrounded by a spiralling disc of gravitationally trapped matter. It keeps swirling until something disturbs the disc and it tumbles into the void.

13 Vesta's giant mountain

Rheasilva peak at the centre of the Rheasilvia crater on the asteroid Vesta is 22 kilometres (13 miles) high, rivalling Mars's Olympus Mons volcano as the tallest peak in the Solar System.

14 Valles Marineris

Valles Marineris is Mars's answer to the Grand Canyon, but on a grander scale. It extends for 3,000 kilometres (1,800 miles), and cuts an eight-kilometre (five-mile) deep scar into the planet's surface. Measuring 600 kilometres (370 miles) across, this canyon is thought to have formed 3.5 billion years ago.

15 Hellas Planitia

Hellas Planitia is an ancient impact crater measuring over 2,000 kilometres (1,200 miles) in diameter, and extending down for four kilometres (2.5 miles). This enormous scar on the southern hemisphere is the largest complete crater on the surface of Mars, created by an asteroid impact around 4 billion years ago.

16 Olympus Mons

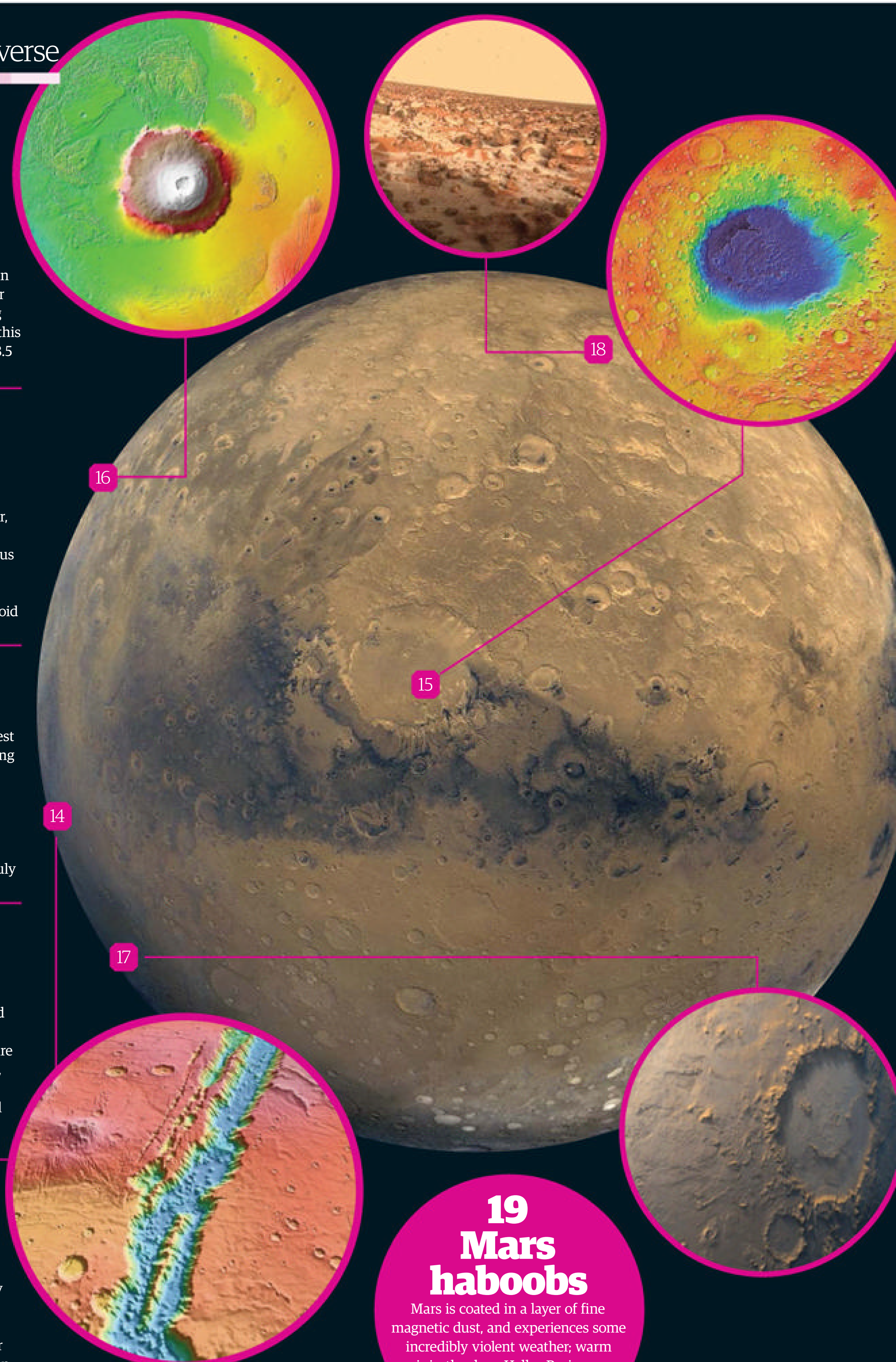
This imposing mountain is the tallest volcano in the Solar System; standing at an incredible 25 kilometres (16 miles) tall. It easily eclipses the tallest volcano on Earth, Mauna Loa. On Mars, the surface is static, so lava continues to erupt in one position, generating a volcano of truly gargantuan proportions.

17 Faces on Mars

When Viking 1 made its mission to Mars in the Seventies it was greeted by a strangely familiar sight; two faces were staring back from the bare rocks on the surface. Unfortunately, high-resolution images of these features revealed both to be natural landforms, and not sculptures created by intelligent life.

18 Utopia Planitia

The crater of this Martian impact basin contains landforms known as 'thermokarst', with geometrically shaped lines and depressions with scalloped edges. When Viking 2 arrived in 1979, it found a thin layer of ice on the surface, and the lines in the ground are thought to have been formed by wedges of subsurface ice.



19 Mars haboobs

Mars is coated in a layer of fine magnetic dust, and experiences some incredibly violent weather; warm air in the deep Hellas Basin can generate storms that engulf the entire planet.

20 Red Square Nebula

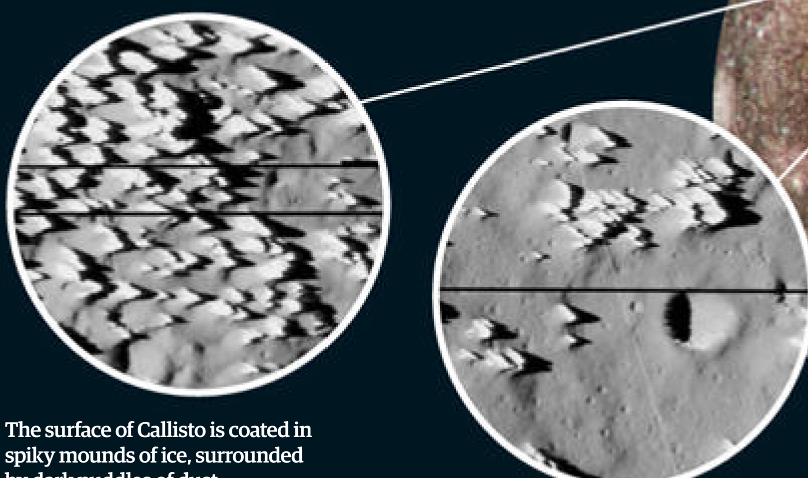
The unusual geometric shape of this nebula found in the constellation of Serpens remains an astronomical mystery, but the leading hypothesis is that we are looking at the side of several cones of gas released by the star or stars sitting at the centre. The cones are at right angles to one another, producing the shape of a square, but if we looked from a different angle we would be able to see directly into one of the cones, and it would appear as a red ring.

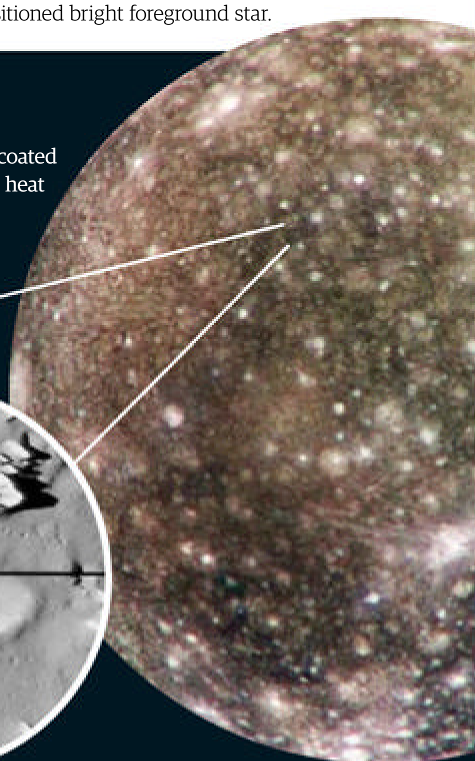
21 The diamond ring

At first glance, this photograph captured by the European Southern Observatory's Very Large Telescope might look like a single object in the form of a cosmic diamond ring, but in reality, it is the result of an interaction between two objects. The ring itself is formed by the blue bubble of a planetary nebula known as Abell 33, created when the atmosphere of a dying Sun-sized star ballooned into space, and the 'diamond' is a well-positioned bright foreground star.

22 Callisto ice spires

Jupiter's moon Callisto was thought to be a dead object, an ancient cratered world coated in a layer of ice, but images captured by NASA's Galileo spacecraft in 2001 revealed spires jutting out from the surface. The icy spikes are coated in dark dust which absorbs heat from the Sun, causing the ice to melt, and gradually eroding the surface.





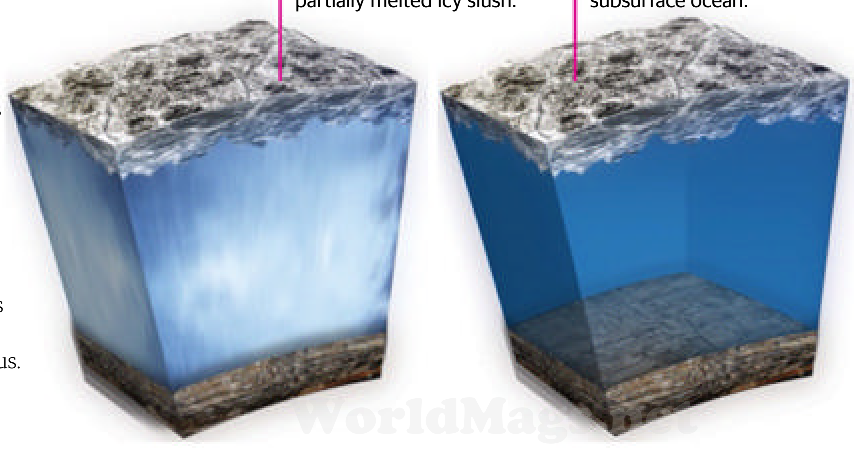
The surface of Callisto is coated in spiky mounds of ice, surrounded by dark puddles of dust

23 Subsurface oceans

Beneath the surface of seemingly frozen moons there are potentially vast quantities of liquid water. In the far reaches of the Solar System the temperature plummets, but friction caused by the gravitational interactions between a moon and its parent planet could melt subsurface ice, resulting in hidden oceans. The tidal motion of these oceans as the moon orbits would help to keep the water in liquid form. The best candidates for subsurface water in the Solar System are Jupiter's moons Europa, Callisto and Ganymede, and Saturn's moons Mimas and Enceladus.

Warm convecting ice
Europa has a magnetic field, indicating that something is conducting electricity below its surface; one explanation is partially melted icy slush.

Liquid ocean under ice
Europa is still warm at its core, so it is thought more likely that the water inside is truly in liquid form, making up a salty subsurface ocean.



24 Dark nebulae

These clouds are so dense that no light can pass through; it is all absorbed, making it appear as though there are gaps in space.

25 Shooting stars

These wonders of the night sky have long fascinated humanity. They happen when chunks of dust and rock burn up as they pass through the atmosphere.

26 Stellar magnets

Magnetars are neutron stars with extreme magnetic fields. They are rare and unpredictable, suddenly erupting with gamma-ray bursts before going quiet.

27 Titan

Saturn's moon Titan is unique in the Solar System; it is the only satellite with its own atmosphere, and is covered in seas of liquid ethane and methane.

28 Tea-temperature star

The nearby brown dwarf star, CFBDSIR 1458+10B, is part of a binary system and has a surface temperature comparable to a freshly made cup of tea.

29 Hypervelocity stars

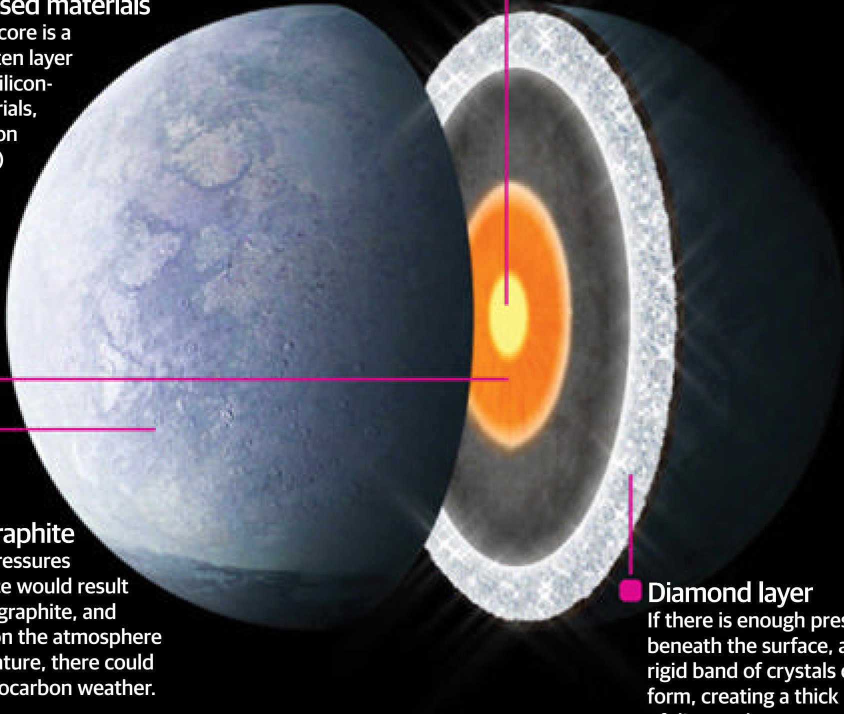
Some stars travel at speeds over 3.2 million kilometres (2 million miles) per hour, fast enough to escape the gravitational pull of their parent galaxy.

30 Himiko

Also known as the Lyman-alpha blob, Himiko is an enormous ancient galaxy; it is so far away that we are looking 800 million years into the past.

31 Hamburger Galaxy

Positioned edge-on to Earth, this spiral galaxy appears to us like a flat red-orange disc of stars and dark dust, reminiscent in shape of a popular American food.



Molten iron core
Like Earth, the core of a diamond planet is thought to be composed of molten iron, or a combination of iron and carbon (molten steel).

Silicon-based materials
Around the core is a second molten layer containing silicon-based materials, such as silicon carbide (SiC) or enstatite ($MgSiO_3$).

Surface graphite
The lower pressures at the surface would result in a layer of graphite, and depending on the atmosphere and temperature, there could also be hydrocarbon weather.

Diamond layer
If there is enough pressure beneath the surface, a rigid band of crystals could form, creating a thick layer of diamond.

32 Diamond planets

Our own Solar System is dominated by oxygen and the terrestrial planets inside it are made from silicon-based rocks. But elsewhere in the universe it is a different story; in carbon-dominated systems, some planets are thought to be made from diamond. One of the first candidates for a diamond planet is a super-Earth known as 55 Cancri E. It is 40,000 light years away, twice the size of Earth and almost eight times the mass, and beneath a surface of graphite, planetary scientists think it could contain a thick shell of precious stones and other crystal structures.

33 Massive water reservoir

The quasar APM 08279+5255 hides a black hole 20 billion times the Sun's mass, and contains an ancient water cloud. The gas surrounding the black hole contains 140 trillion times more water than Earth's oceans.

34 Gamma-ray bursts

Once a day, a random point in the sky blazes with an intense pop of energy known as a gamma-ray burst. Each burst is thought to be the final firework display of a massive star as it collapses down to form a black hole.

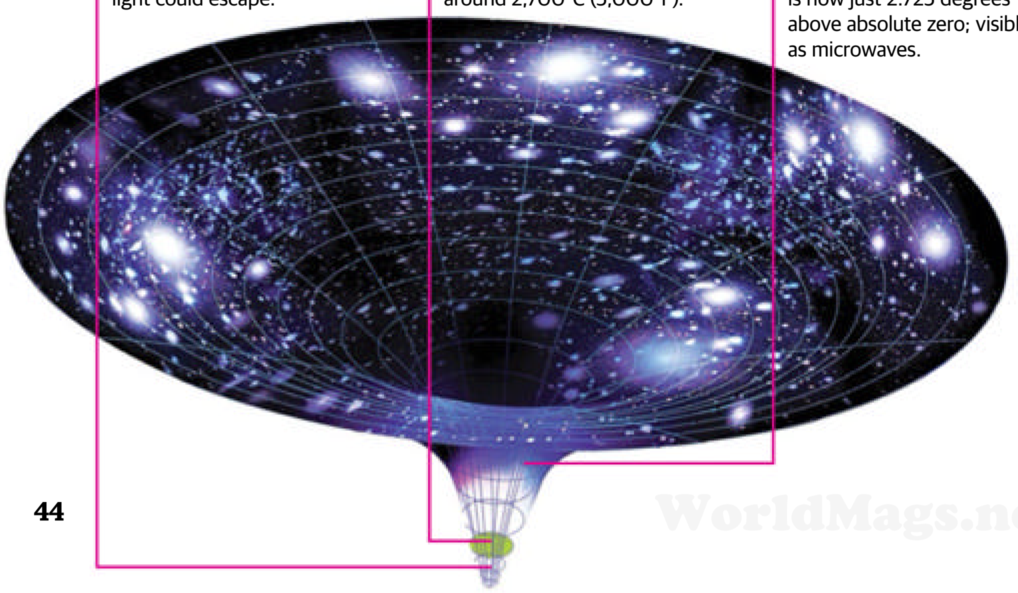
35 Cosmic Microwave Background

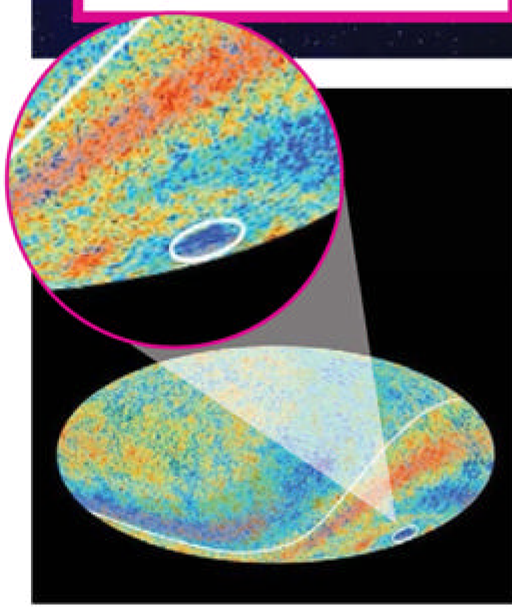
The cosmic microwave background (CMB) is evidence of the Big Bang written all over the fabric of the universe. It was discovered by Bell Telephone Laboratories in the Sixties, and was originally little more than a nuisance, interfering with radio communications, but it soon became clear that this background radiation was special. The CMB represents the oldest light in the universe; the thermal radiation left over from the Big Bang. The early universe was hot and dense but over the last 13.7 billion years, it has stretched and cooled. As the universe has expanded, the heat signature expanded with it, leaving behind a visible fingerprint in the form of a uniform layer of microwave radiation spread across the sky.

Very early universe
In the earliest stages of the universe, it was so hot and dense that free electrons scattered photons, and no light could escape.

Creation of the CMB
The first light of the universe was released 380,000 years after the Big Bang, when the universe had cooled to around 2,700°C (5,000°F).

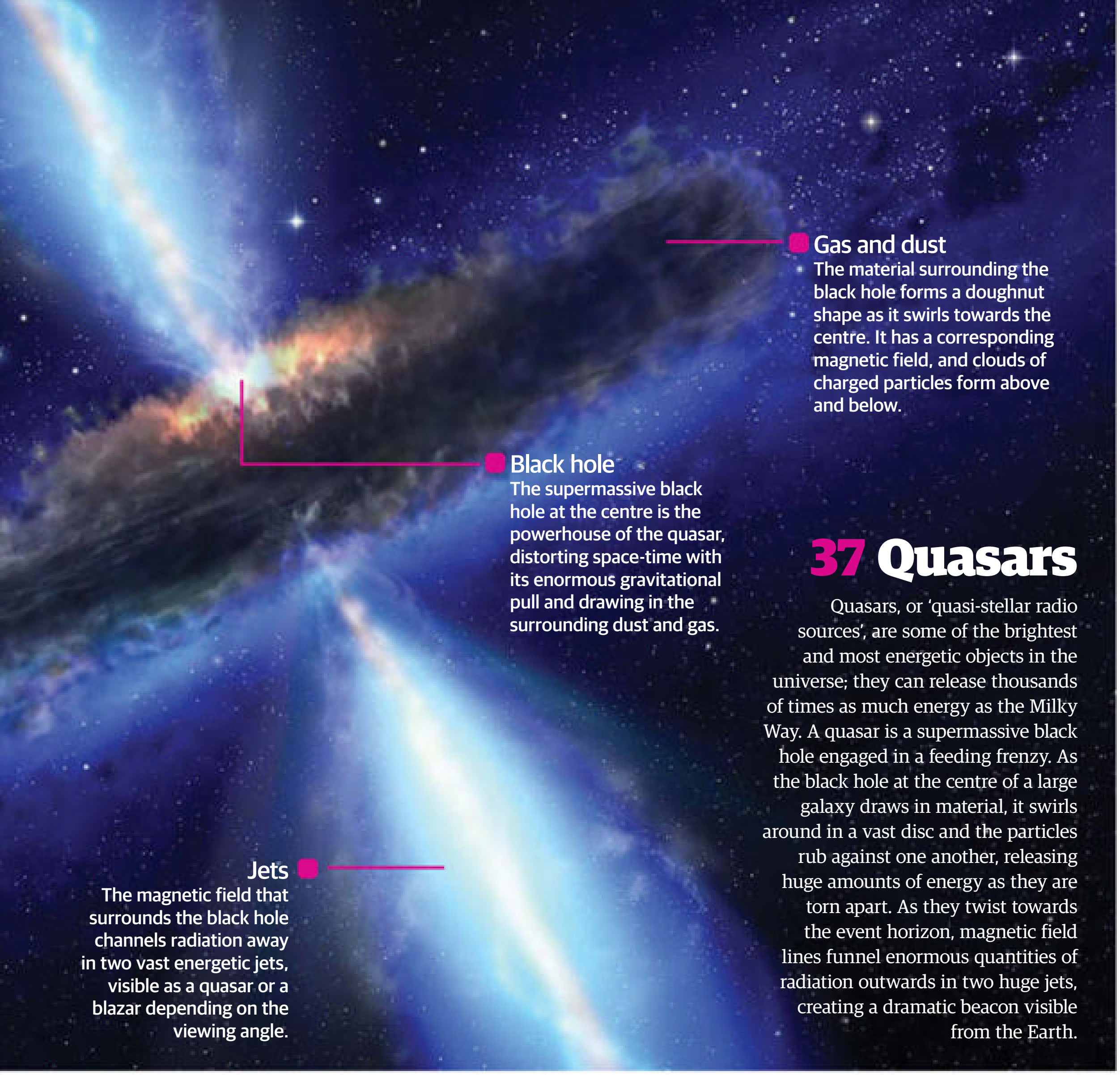
Expansion
As the universe has continued to expand, the first light has expanded with it, and the thermal signature is now just 2.725 degrees above absolute zero; visible as microwaves.





36 The Cold Spot

The Cosmic Microwave Background (CMB) (see wonder number 35), is the afterglow of the Big Bang, and is relatively uniform across the entire sky, however there is a strange cold spot in the lower right-hand corner. The chance of this happening at random is around 1 in 100, and its presence is puzzling cosmologists. Possible explanations put forward include an enormous supervoid, a defect known as 'texture', and even the presence of a parallel universe.

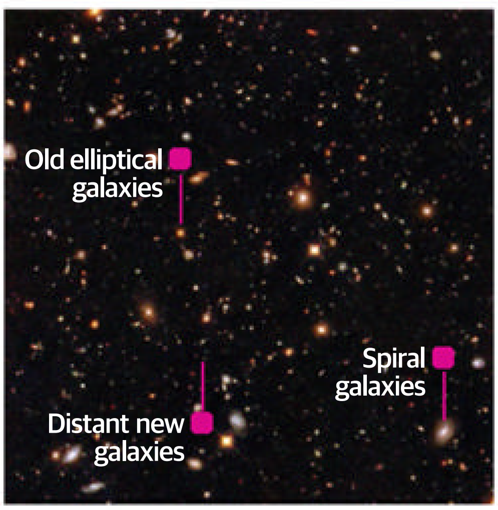


37 Quasars

Quasars, or 'quasi-stellar radio sources', are some of the brightest and most energetic objects in the universe; they can release thousands of times as much energy as the Milky Way. A quasar is a supermassive black hole engaged in a feeding frenzy. As the black hole at the centre of a large galaxy draws in material, it swirls around in a vast disc and the particles rub against one another, releasing huge amounts of energy as they are torn apart. As they twist towards the event horizon, magnetic field lines funnel enormous quantities of radiation outwards in two huge jets, creating a dramatic beacon visible from the Earth.

38 Hubble Deep Field

One of the most astonishing things about space is what appears when you point a telescope at nothing. Between 2003 and 2004, the Hubble Space Telescope was aimed at an empty portion of the sky in the constellation of Fornax and in the eight years that followed, it kept returning, creating an even more detailed image of what appeared to be a blank patch of sky. The resulting images revealed a sea of galaxies, stretching back in space and time 13.2 billion light years, almost to the birth of the universe.



39 Stephan's Quintet

This cluster of five galaxies was discovered in the 19th century and demonstrates the effects gravity on a monumental scale. Three of the galaxies are so close that immense gravitational tides have made visible changes to their structure, pulling on their spiral arms and distorting their shapes as they twist towards an inevitable collision. The bluer galaxy at the bottom left of the image is an interloper, 240,000 light years away from the others, it is not actually part of the group.

40 Dark energy

We know little about dark energy other than that it is accelerating the expansion of that which followed the Big Bang. It is thought to make up between 68 and 71 per cent of the universe.

41 Dark matter

Between 24 and 27 per cent of the universe is thought to be composed of dark matter, made up of subatomic particles that interact only weakly with 'ordinary' matter.

42 Rare types of matter

'Normal' atomic matter, made up of protons and neutrons makes up just five per cent of the universe. The remainder is dark matter and dark energy, neither of which have ever been directly detected.

43 Red dwarfs

These small, dim stars burn so slowly that they are thought have lifespans longer than the total age of the universe, meaning that none are yet old enough to have died.

44 Asteroid belt

Between Mars and Jupiter lies a band of leftovers from the beginnings of the Solar System; either the remnants of a planet that failed to form, or the fragments of a broken one.

45 Oort cloud

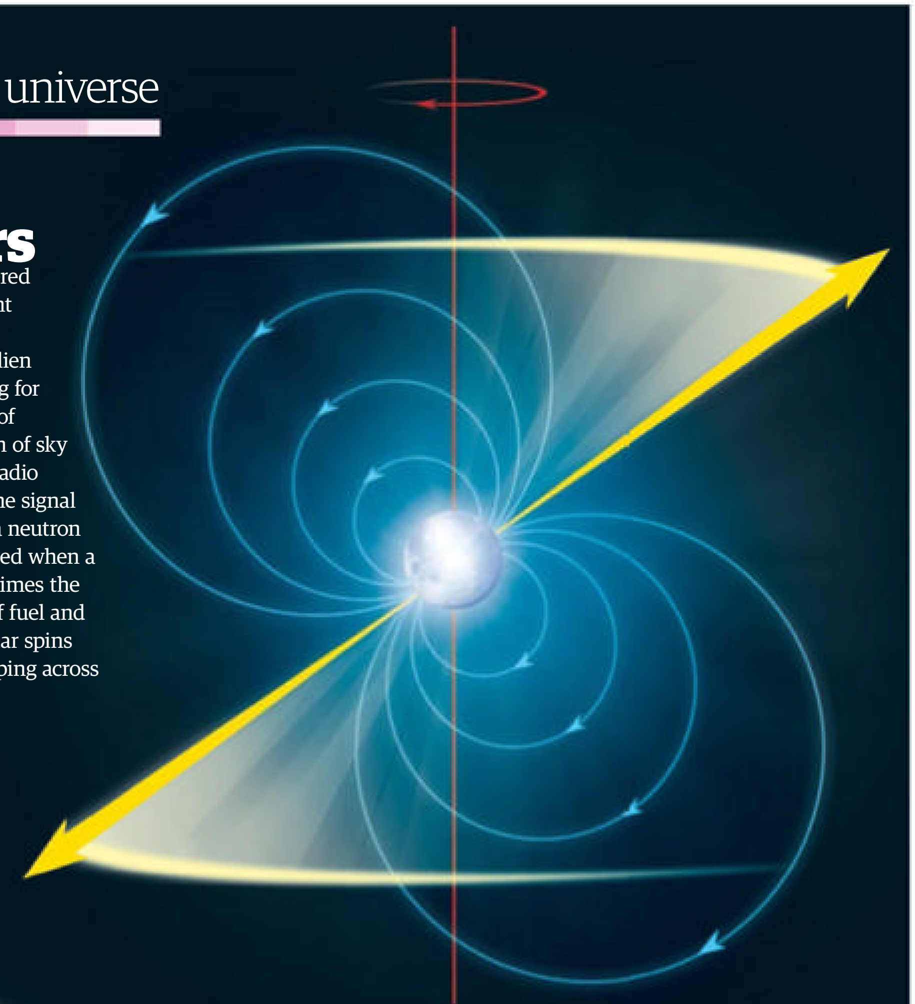
The Solar System is encased in a sphere of icy objects, collectively known as the Oort cloud. The Sun's gravity at that distance is so weak that passing objects can send comets hurtling inwards.

46 Backwards spiral galaxy

The arms of spiral galaxies trail backwards as they turn, but NGC 4622 is turning in the same direction that its arms point, possibly as the result of a collision that upset its spin.

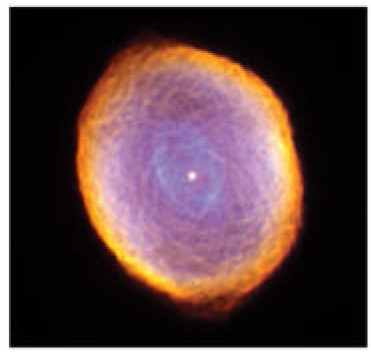
47 Pulsars

When pulsars were discovered in 1967, Jocelyn Bell thought she might have intercepted communications from an alien civilisation. While searching for the high-energy twinkling of quasars, she noticed a patch of sky emitting regular pulses of radio waves every 1.3 seconds. The signal was actually generated by a neutron star. Neutron stars are created when a star between eight and 25 times the mass of the Sun runs out of fuel and collapses. As the neutron star spins its radio jets spin too, sweeping across the sky in regular pulses.



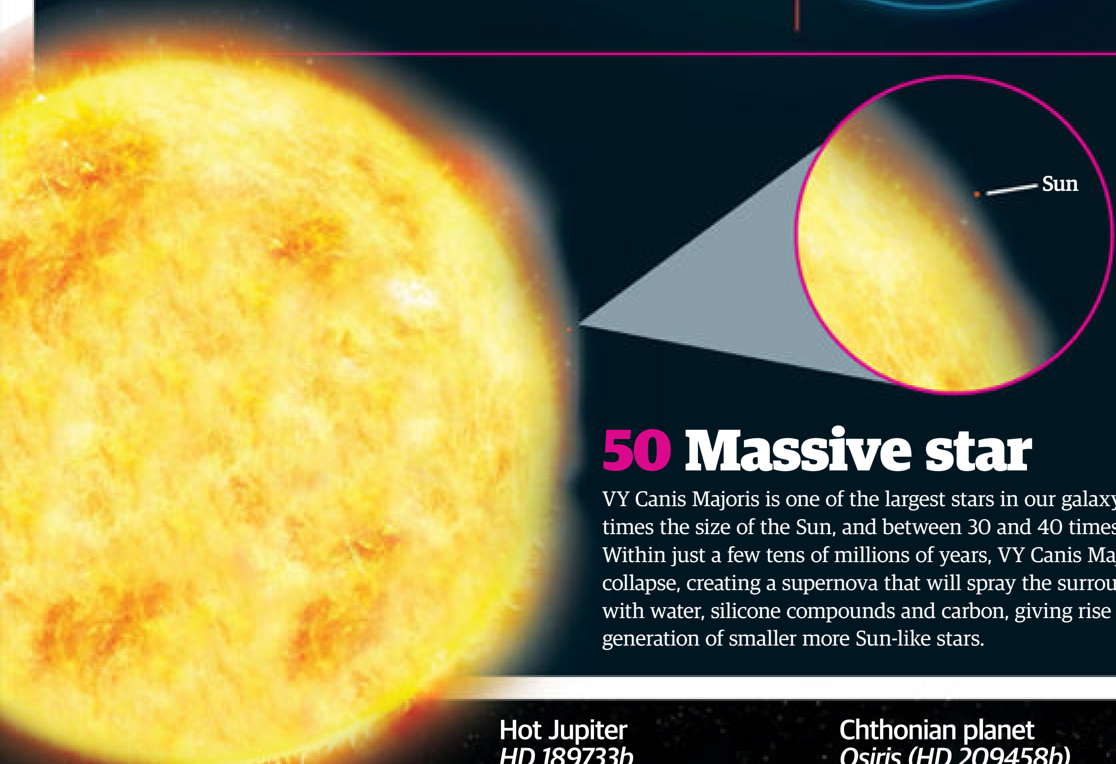
48 Hoag's Object

This unusual object is a ring galaxy, one of the rarest galaxy types in the universe. At the centre is a spherical bulge of old orange-red stars, and around the edges is a ring of bright blue hot young stars. Other ring galaxies are thought to have formed following a collision, or due to a rapidly spinning central bar, but the origin of Hoag's Object is unknown. If you look inside, another ring galaxy is visible far in the distance.



49 Spirograph Nebula

The star at the centre of these geometric swirls used to be like our own Sun, but a few thousand years ago it started running out of fuel and ballooned to become a red dwarf. Since then, its fuel has disappeared, and its envelope has begun expanding. The white dwarf now forming at the centre is unpredictable, and scientists believe that its erratic winds could be making these strange patterns in its nebula.



50 Massive star

VY Canis Majoris is one of the largest stars in our galaxy; 2,000 times the size of the Sun, and between 30 and 40 times the mass. Within just a few tens of millions of years, VY Canis Majoris will collapse, creating a supernova that will spray the surrounding space with water, silicone compounds and carbon, giving rise to a new generation of smaller more Sun-like stars.

51 Exoplanets

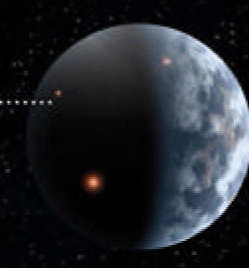
Until 1994, the planets of the Solar System were the only planets that we were aware of in the universe. It was always thought likely that other stars had companions. The first exoplanet was found orbiting a pulsar and, just a year later, in 1995, another was discovered orbiting a Sun-like star. NASA's JPL lists a total of 5,003 known exoplanets.

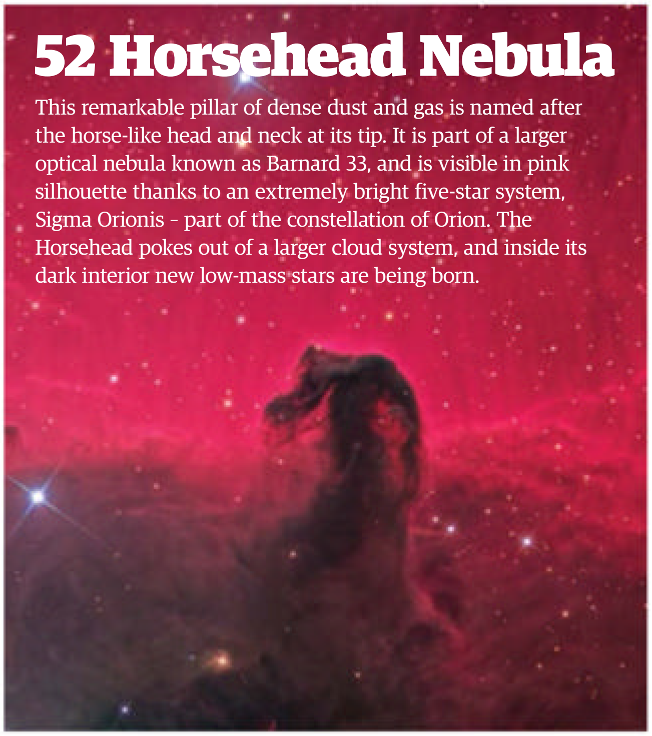
Hot Jupiter
HD 189733b
These enormous gas giants orbit close to their parent stars, blocking the light as they pass and making their presence easy to detect. Some, like HD 189733b, orbit closer than Mercury.

Chthonian planet
Osiris (HD 209458b)
Gas giants orbiting close to their stars are bombarded by radiation and solar winds, and evaporate rapidly. Chthonian planets are the hypothetical rocky remnants that will be left behind.

Hot Neptune
Gliese 436 b
These Neptune-sized planets orbit close to their parent stars, and a year on the surface passes quickly, making them easy to detect from far away.

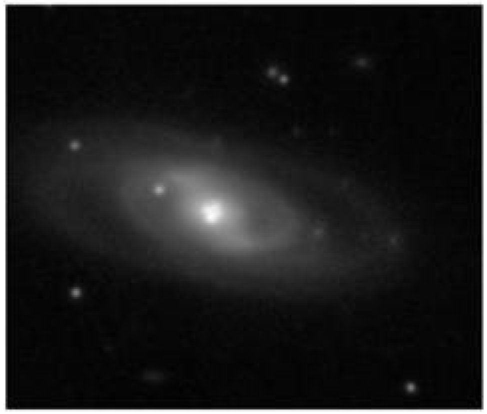
Water world
Kepler 22b
This group of ocean planets are composed mostly of water. Some are thought to have thick atmospheres, supporting liquid water on the surface, but others are hot, steamy and unstable.





52 Horsehead Nebula

This remarkable pillar of dense dust and gas is named after the horse-like head and neck at its tip. It is part of a larger optical nebula known as Barnard 33, and is visible in pink silhouette thanks to an extremely bright five-star system, Sigma Orionis - part of the constellation of Orion. The Horsehead pokes out of a larger cloud system, and inside its dark interior new low-mass stars are being born.



53 Einstein Cross

One of Albert Einstein's greatest ideas was that the universe is made from a fabric called space-time, and that mass causes this fabric to bend, like balls sitting on a trampoline. Incredibly, there is evidence of it happening right before our eyes. The Einstein Cross is a single quasar, but it looks like four because a galaxy sitting in front of it bends space-time, curving the light as it passes, and acting like a lens to duplicate the image.

54 Caloris Basin

This enormous impact basin measures 1,500 kilometres (930 miles) in diameter, and is one of the hottest places on Mercury. Its perimeter is studded by volcanic vents, visible here as bright orange hot spots, and its interior is pockmarked by hundreds of more recent impacts.

55 Mercury double sunsets

When Mercury is at its closest point to the Sun, it travels so quickly that its rotational speed can't keep up, and after the Sun sets it reappears and sets again.

56 Aurorae

The aurora borealis and the aurora australis are some of nature's most spectacular wonders. The Sun releases a stream of charged particles called the solar wind, and this feeds into the magnetosphere around our planet, dislodging other particles and slamming into the gases that make up the atmosphere. These collisions excite the gas molecules, and make them glow. Depending on the height and the type of gas hit different colours are made.

57 Supernovae

When massive stars die they go out with a bang, releasing as much energy as the Sun will during its entire lifetime in just fractions of a second.

58 South Pole-Aitken Basin

The south pole of the Moon has a spectacular impact crater, covering an area measuring around 2,600 kilometres (1,600 miles), and deeper than the height of Mount Everest.

59 Chelyabinsk meteorite

This 19-metre (62-foot) wide asteroid exploded in mid-air over Russia in 2013; an event that happens on this scale approximately once every 30 years.

60 Cataclysmic variable stars

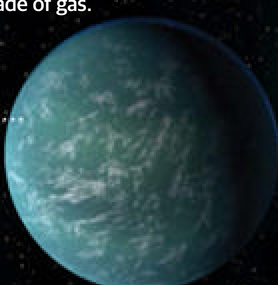
In some binary systems, a white dwarf and a larger star, like a red giant, orbit close to one another. The white dwarf feeds on its companion, creating an accretion disc that glows.

61 Total solar eclipse

These rare events are only possible thanks to the chance position of the Moon; at its current distance, the Moon appears the perfect size in the sky to completely cover the Sun's disc as they line up. Read more about them in our feature on page 64.

Super-Earth
HIP 116454b

These planets have a mass greater than Earth, but lower than Neptune. Despite the name, not all super-Earths are Earth-like - some are blisteringly hot, others are frozen, and some are made of gas.

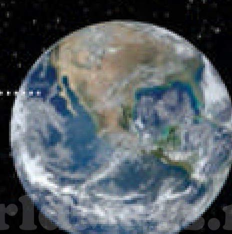


Gas giant
GJ 540b

These enormous planets, just like Jupiter and Saturn, are several times the mass of Earth, and are composed mostly of gas, with a molten rocky or metallic core.

Terrestrial
55 Cancri e

These are the planets that, like Earth, are composed mainly of rocks or metals. It is thought that there could be as many as 40 billion habitable terrestrial planets in the Milky Way alone.



Brown dwarf
Teide 1

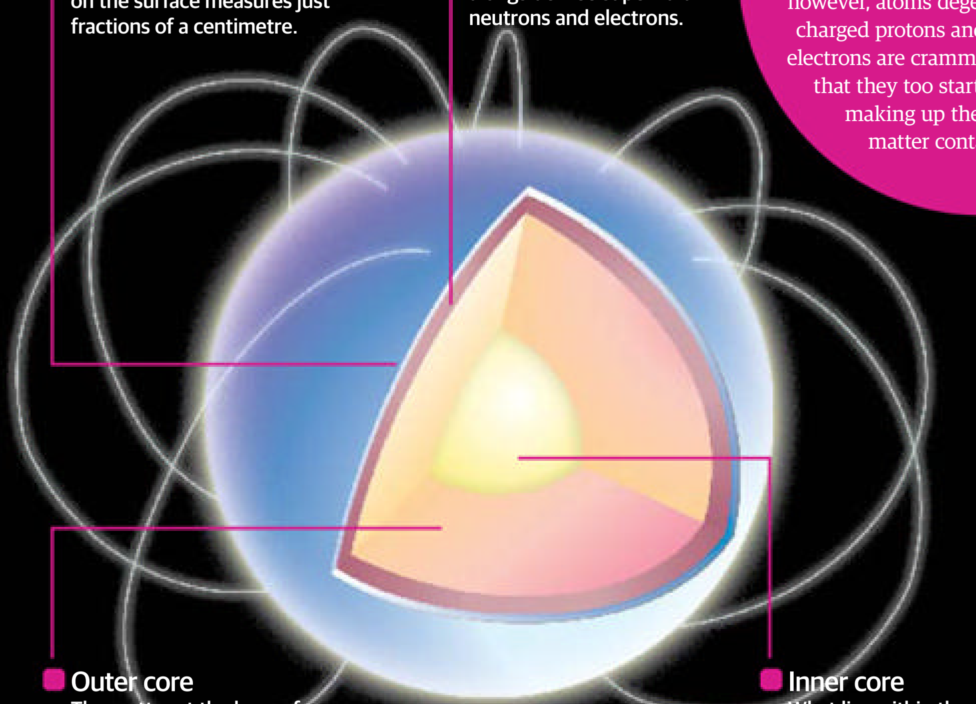
These objects are larger than planets, but smaller than stars. With a mass in between, they were unable to sustain a nuclear fusion reactor that makes a star, and are sometimes known as 'failed stars'.

Rogue planet
WISE 0855-0714

Rogue planets do not orbit their parent star. Instead, they orbit the centre of their galaxy directly, still warmed by their molten cores, but often encased in ice.

62 Neutrons

Neutrons are subatomic particles of neutral charge, and in normal matter they make up part of the atomic nucleus, sitting alongside positively charged protons. Under the immense pressure inside a neutron star however, atoms degenerate and positively charged protons and negatively charged electrons are crammed together so tightly that they too start to form neutrons, making up the bulk of all the matter contained inside.

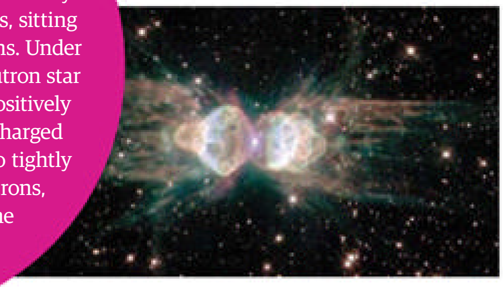


63 Neutron stars

When a massive star runs out of fuel, the outwards explosive force that opposes the inwards crunch of gravity is removed, and in just fractions of a second, the structure collapses. Very large stars collapse entirely to form black holes, but smaller stars still retain a shred of their former presence in the shape of a neutron star. They are the size of a city, but contain the mass of around 500,000 Earths, and are so dense that a single teaspoonful of their matter would weigh ten million tons.

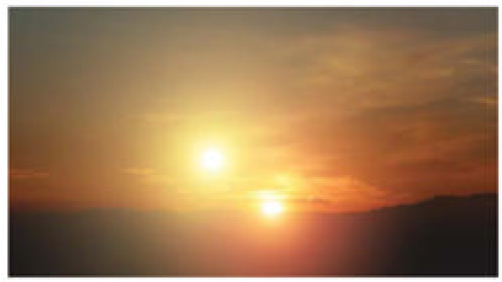
66 Orion Nebula

The astonishing colours of the Orion Nebula have made it one of the most famous sights in the sky. Just 1,500 light years from the Earth, the glowing red cloud of ionised hydrogen is dominated by a group of three enormous stars collectively known as the Trapezium. The nebula is just 30,000 years old, and is a place of intense star birth. The hot young Trapezium stars have blown a hollow in their dust shroud, and are illuminating the surrounding cloud.



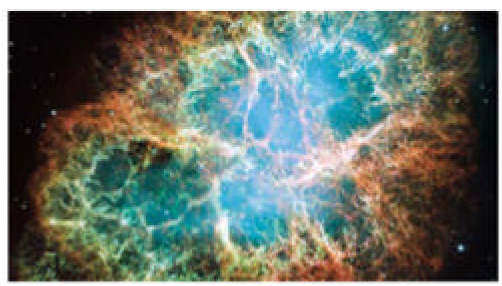
64 Ant nebula

This object bears a striking resemblance to the head and thorax of an ant, but look closely and a dying star is visible at its core; between the two segments, a star not unlike our Sun is in the midst of collapse. The shape of its explosion has puzzled astronomers, and rather than being uniform in all directions, the gas is wound up into two symmetrical lobes. It is thought that there may be another star, stirring the gas with its gravitational pull, or that the spin of the dying star could be creating these enormous swirls.



65 Twin stars

Around 85 per cent of the stars in the Milky Way are thought to move in pairs, threes, or in larger groups. They are known as binary or multiple star systems, and instead of existing alone, the companions orbit around a common centre of mass. Some pairs can easily be seen through a telescope, while others look like one bright star, but can be distinguished by fluctuations in the colour of their light as they orbit, and some pass in front of one another, producing measurable eclipses that can be seen from Earth.



67 Crab Nebula

This five light year-wide nebula is the remnants of a supernova explosion that lit up the southern sky in 1054 CE. The gas cloud is expanding at a rate of around 1,800 kilometres per second (1,100 miles per second), and the gas creates a glowing rainbow. In the interior, the blue and green filaments are oxygen and sulphur, and towards the edges, the orange and red are hydrogen and oxygen. At the very centre, electrons glow blue as they circle the magnetic field of a neutron star.

68 Whirlpool Galaxy

This near-perfect swirl is a classic example of a spiral galaxy. Like our own galaxy, bright blue stars are formed within the enormous arms, twisting around a central bulge of older orange-red stars in the last phases of their existence. The spirals are lined with dust lanes composed of dark silicon and carbon, and clouds of hydrogen gas glow red as they are excited by the light from the young stars.

69 Space volcanoes

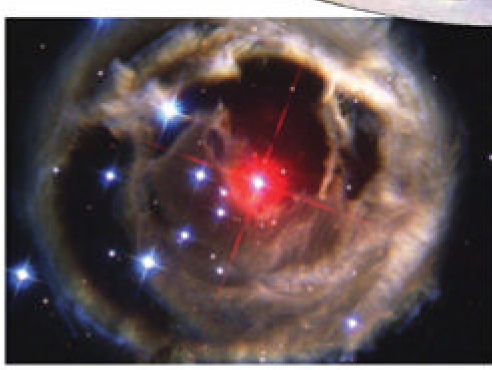
The Solar System is full of volcanic activity. The largest volcano of all, Olympus Mons, is located on Mars, and Venus boasts the highest number of volcanoes of any planet, with over 1,600 major volcanic features, and tens of thousands of smaller volcanoes. Though neither planet has seen recent volcanic activity, it is possible that some are still active. Volcanoes are not just restricted to planets; Jupiter's moon Io is more volcanically active than Earth, and Neptune's moon Triton and Saturn's moon Enceladus both harbour cryovolcanoes, which spew not lava but water. The gravitational pull of the parent planet of each moon warps their shape, causing their internal structure to melt and flex, and resulting in violent eruptions.

70 Io

Jupiter's third largest moon, Io, is the most volcanically active place in the Solar System, capable of jettisoning lava 300 kilometres (190 miles) into the sky. Its atmosphere is thin and sulphurous, and its surface is constantly being smoothed and remodelled by lava flows. Incredibly, Io acts as a lightning rod, and as it dips through Jupiter's magnetic field it generates currents of up to 3 million amperes, which zip down towards the surface of the gas giant below.

71 Light 'echoes'

In early 2002, the star V838 Monocerotis suddenly became incredibly bright, and then rapidly dimmed again in an unprecedented display that stumped astronomers. During the event, which is known as a 'light echo', the star grew hugely in diameter, but unlike other ageing stars, it did not lose its outer layers and instead they cooled until its surface was almost cold enough to touch. The light emitted was reflected by dust that the star had already expelled, revealing layers of previously invisible swirls.



72 Globular clusters

These dense symmetrical spheres contain ancient red-orange stars, and are the oldest subsystems inside galaxies, thought to have formed between 13 and 15 billion years ago.

73 Reflection nebula

These nebulae do not emit any light of their own, but they reflect light from nearby stars, revealing their dusty outlines.

74 Asteroid moons

It is not just planets that have satellites, around 16 per cent of large near-Earth asteroids have one, or even two, moons of their own.

75 Cosmic voids

The structure of the universe looks something like a three-dimensional web, with most of the galaxies arranged into clumps and filaments. In between, there are vast holes.

76 Wolf-Rayet stars

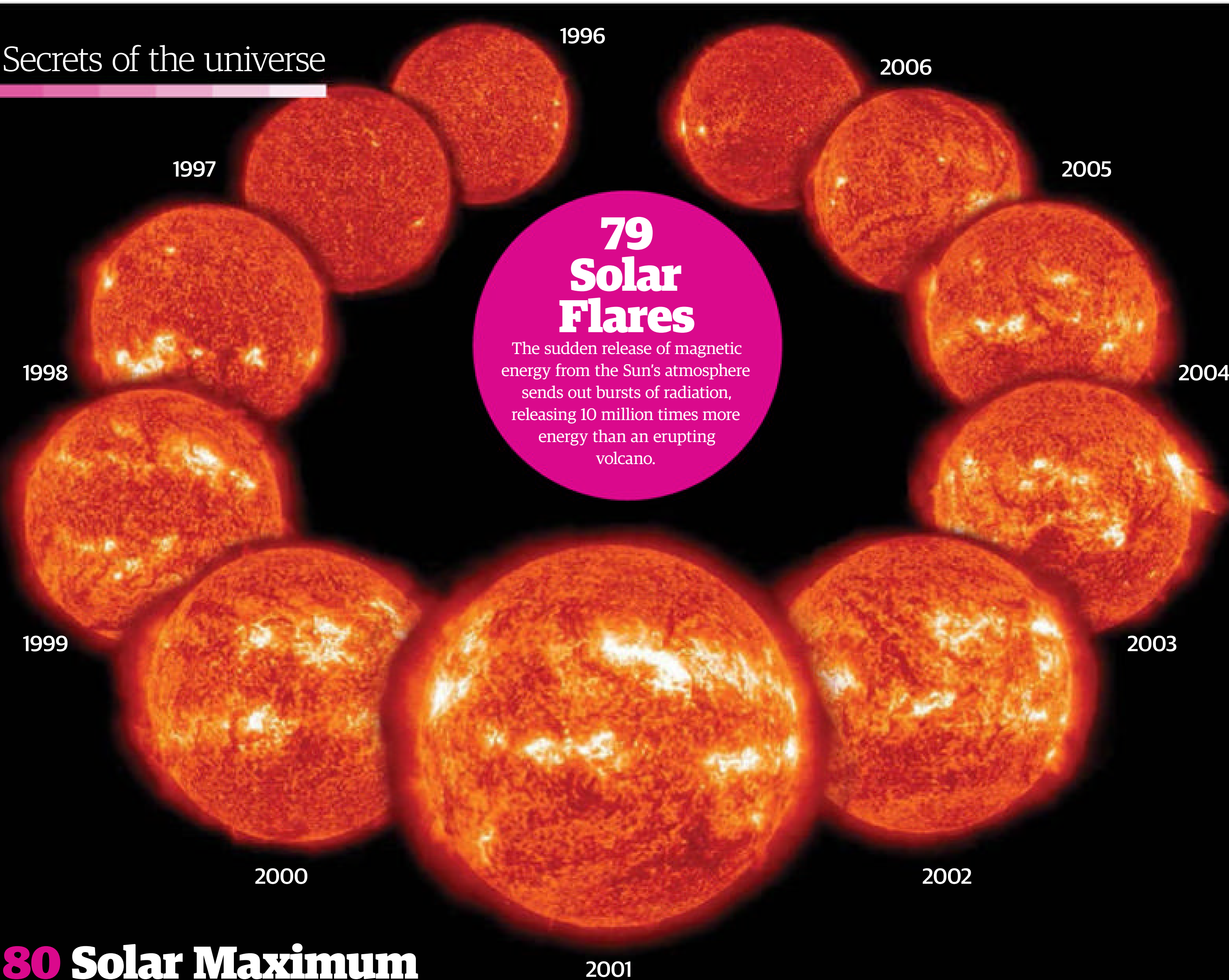
These hot, massive stars are nearing the end of their lives, and have started losing their atmosphere at an astonishing rate as solar winds blow their gases out into space.

77 Ceres

Ceres is the largest object in the asteroid belt; its growth was stunted by the gravity of Jupiter, and at only 950 kilometres (590 miles) across, it is known as an embryonic planet.

78 Large quasar group

The largest structure in the known universe is a cluster of quasars, the violent nuclei of early galaxies, stretching in a chain that covers 4 billion light years.

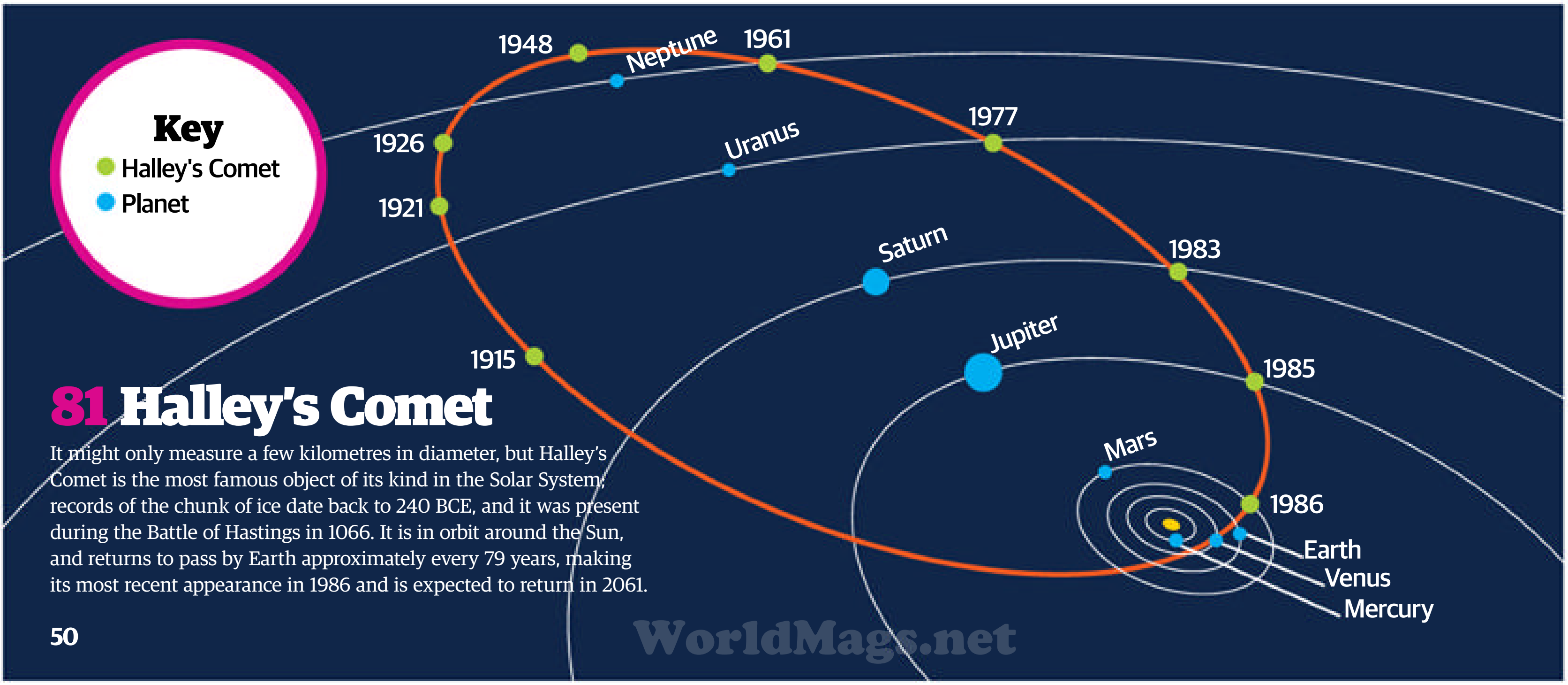


79 Solar Flares

The sudden release of magnetic energy from the Sun's atmosphere sends out bursts of radiation, releasing 10 million times more energy than an erupting volcano.

80 Solar Maximum

The Sun is a consistent presence in Earth's sky, but it isn't quite as constant as it might appear. Its magnetic flux varies on an approximately 11-year cycle, and at its peak, known as the solar maximum, sunspots are visible on its surface almost continuously. In areas where the Sun's magnetic field is at its strongest, the temperature plummets; this creates visible dark spots, some of which can measure 50,000 kilometres (31,000 miles) across. During the solar maximum, the number of these spots rises, appearing in two bands one either side of the equator, and these active regions are often associated with solar flares and coronal mass ejections, which start to ramp up as the solar maximum passes.

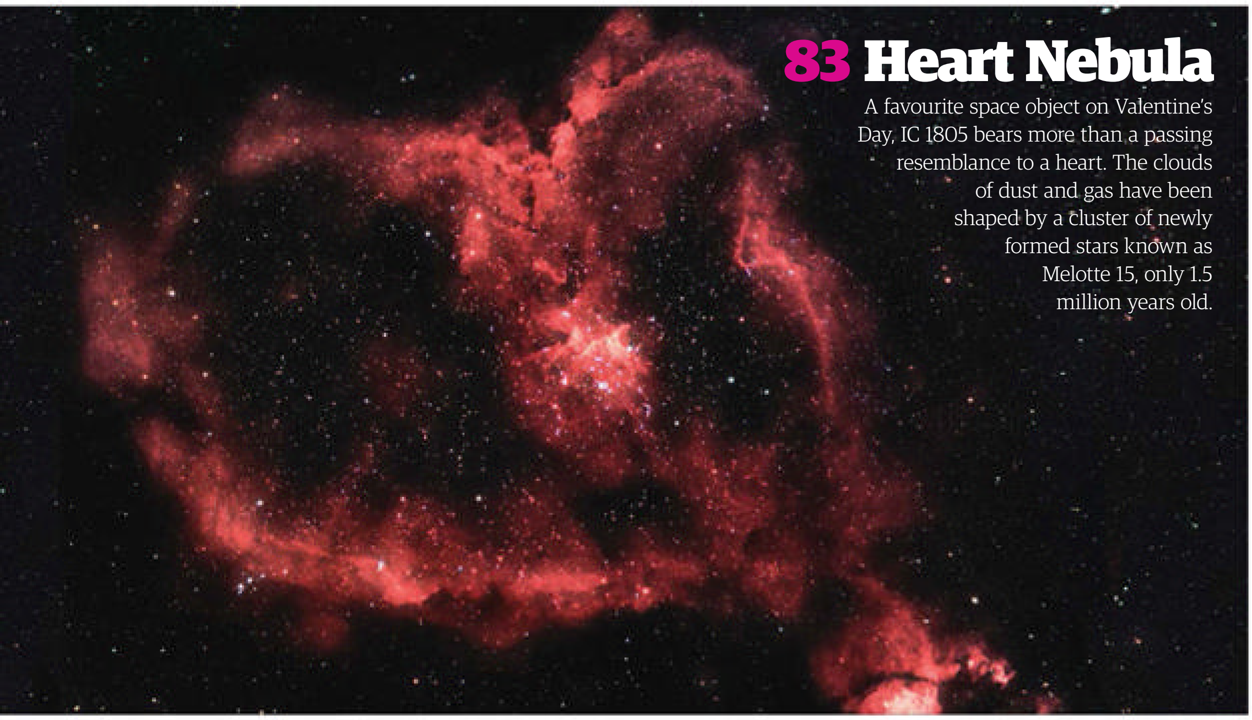


81 Halley's Comet

It might only measure a few kilometres in diameter, but Halley's Comet is the most famous object of its kind in the Solar System; records of the chunk of ice date back to 240 BCE, and it was present during the Battle of Hastings in 1066. It is in orbit around the Sun, and returns to pass by Earth approximately every 79 years, making its most recent appearance in 1986 and is expected to return in 2061.

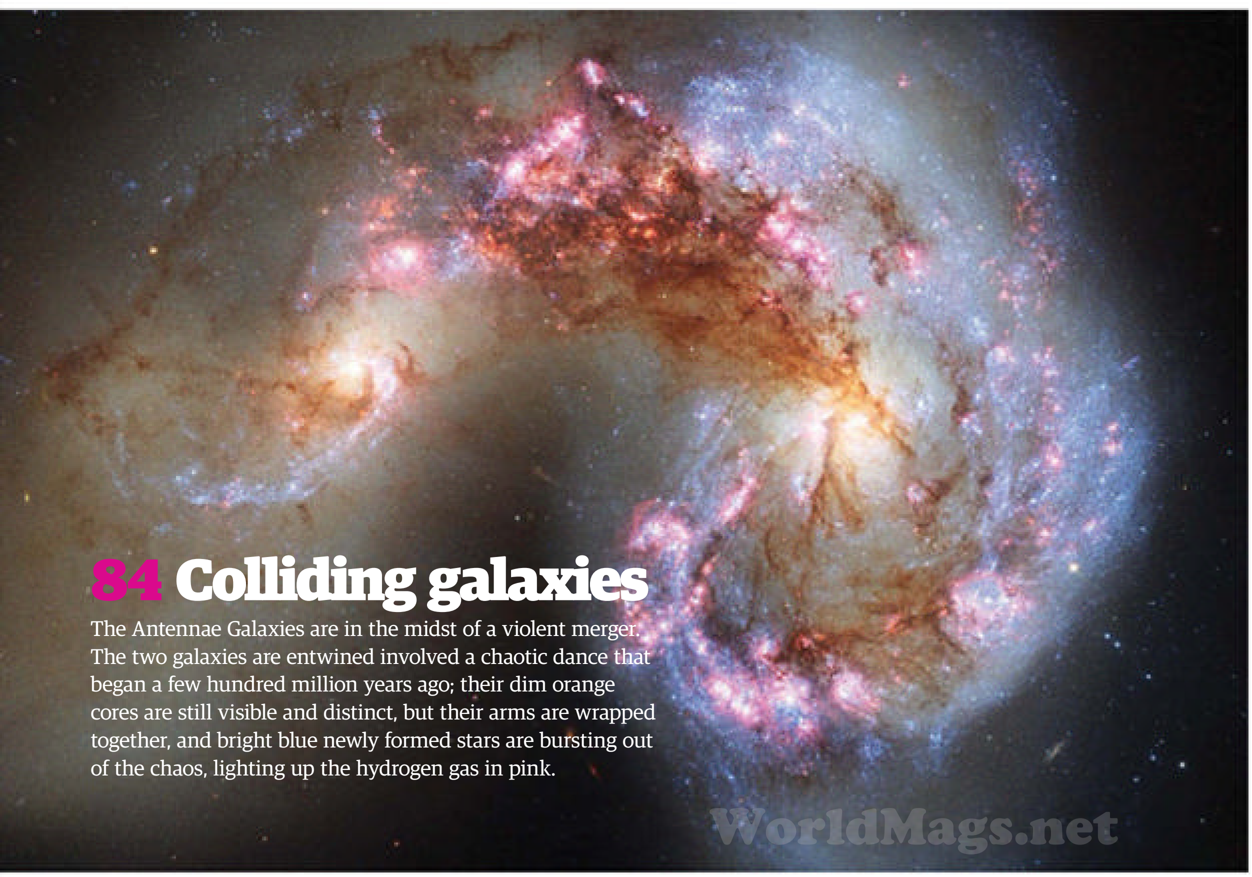
82 Cigar Galaxy

This edge-on spiral is known as a starburst galaxy, and is a hive of star formation activity. The new stars are fuelled by supernovae, and several have been observed over the last few decades. The most recent in the area occurred in 2014.



83 Heart Nebula

A favourite space object on Valentine's Day, IC 1805 bears more than a passing resemblance to a heart. The clouds of dust and gas have been shaped by a cluster of newly formed stars known as Melotte 15, only 1.5 million years old.



84 Colliding galaxies

The Antennae Galaxies are in the midst of a violent merger. The two galaxies are entwined involved a chaotic dance that began a few hundred million years ago; their dim orange cores are still visible and distinct, but their arms are wrapped together, and bright blue newly formed stars are bursting out of the chaos, lighting up the hydrogen gas in pink.

85 Micro black holes

These hypothetical black holes are thought to have formed early in the history of the universe, and contain the mass of a mountain crammed into the volume of just one atom.

86 Neutrinos

These subatomic particles are made in violent explosions, but with no mass and no charge they can travel through objects, reaching Earth and pointing us back to their source.

87 Hot ice planets

The temperatures on the planet GJ 436b are well above the boiling point of water, but the pressure is so high that it has turned to an exotic form of ice.

88 Dune fields

Despite their differences, Earth, Venus, Mars and Titan all share a common feature; wind in the atmosphere of each has swept the surface dust into rippling dunes.

89 The hole in space

We're located inside a hole in the interstellar medium known as the Local Bubble, formed by a group of exploding supernovae around 10 million years ago.

90 Pole stars

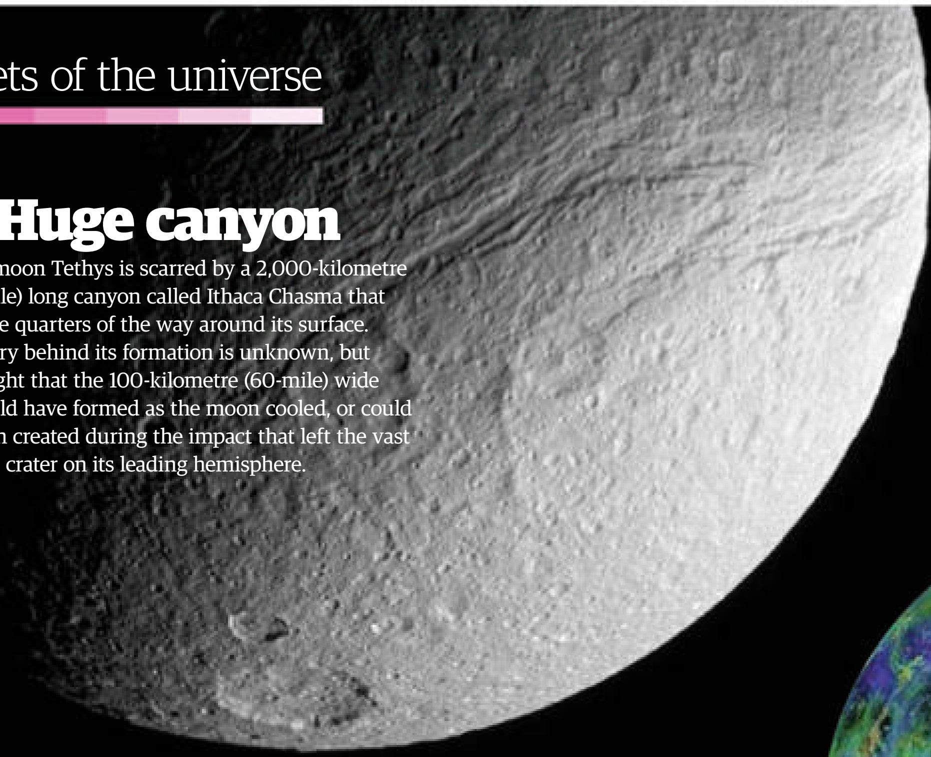
Polaris is the current North Star and is almost lined up with magnetic north, but the Earth's axis spins in a cone-shape every 26,000 years, so this won't always be the case.

91 Rum cloud

Sagittarius 2b, a cloud near the centre of the Milky Way, has 10 billion, billion, billion litres of alcohol, along with a molecule called ethyl formate, which smells like rum.

92 Dinosaur crater

Chicxulub is a 66-million-year-old impact crater in Yucatan, Mexico. It is the site of the asteroid impact that let to the mass extinction event that killed the dinosaurs.

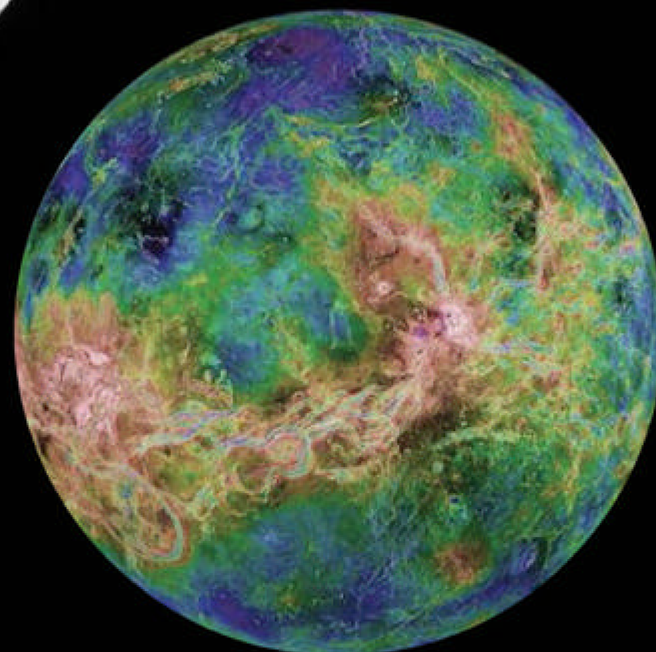


93 Huge canyon

Saturn's moon Tethys is scarred by a 2,000-kilometre (1,200-mile) long canyon called Ithaca Chasma that runs three quarters of the way around its surface. The history behind its formation is unknown, but it is thought that the 100-kilometre (60-mile) wide crack could have formed as the moon cooled, or could have been created during the impact that left the vast Odysseus crater on its leading hemisphere.

94 Giant river bed

Baltis Vallis is a 6,800-kilometre (4,200-mile) channel on Venus. It is the longest in the Solar System, challenged only by the River Nile in Egypt, which measures around 6,650 kilometres (4,132 miles) from start to finish. At between one and three kilometres (0.6 and 1.8 miles) wide, Baltis Vallis is thought to have been formed by fast-moving lava flows, and resembles a river in the way that it winds across the landscape.

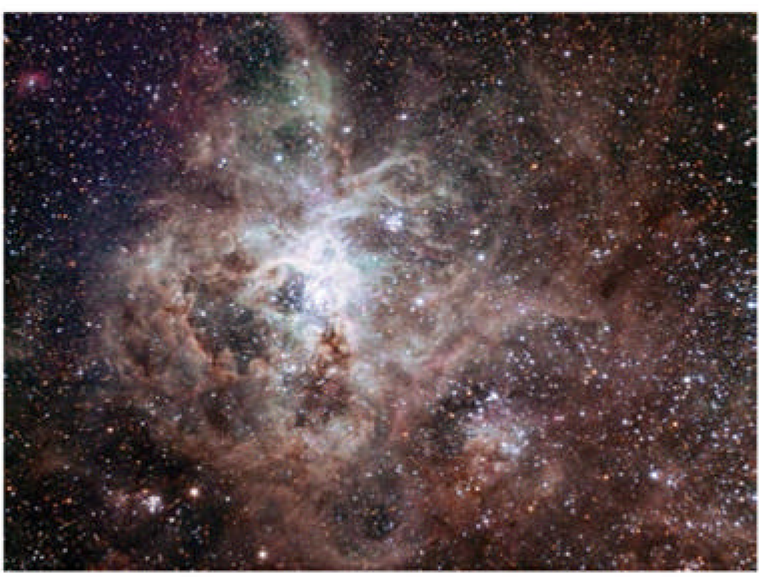


95 Painted moon

The surface of Saturn's moon Iapetus is half black and half white, earning it the nickname 'painted moon'. Its strange colouration is thought to be down to debris sprayed onto its face by other moons. As the dark material is heated by the Sun, any ice trapped with it turns to vapour, leaving just the sooty debris behind and preventing the 'paint' being covered with bright ice.

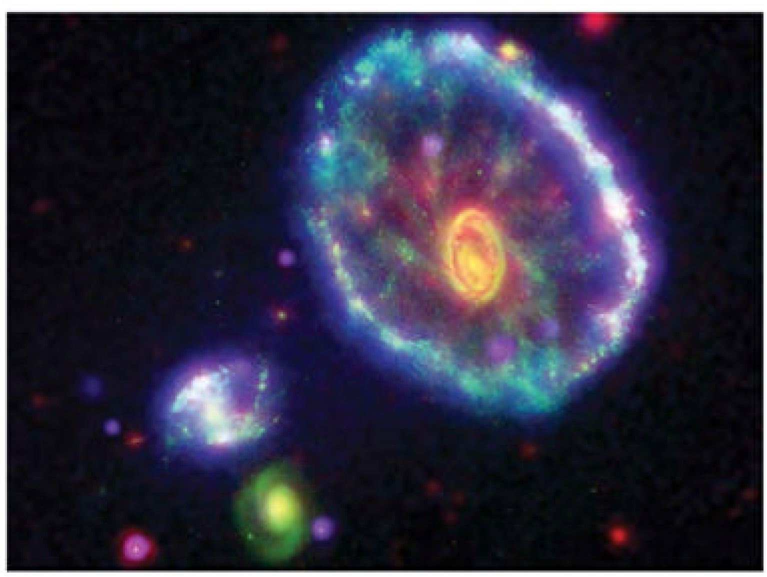
96 Tarantula Nebula

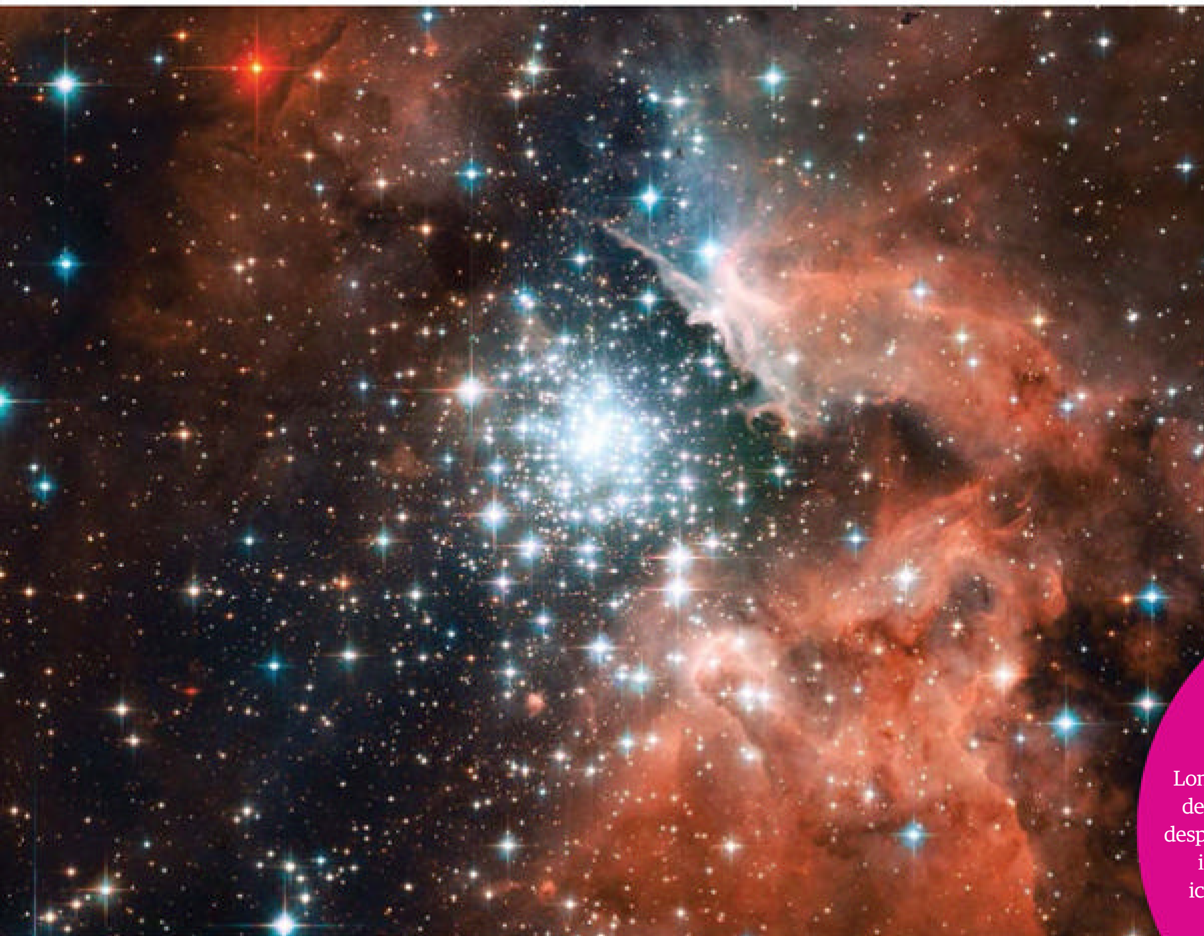
The wispy arms of the Tarantula Nebula are made from partially ionised hydrogen gas, excited by a supercluster of massive stars called R136. It is the largest star-forming region in nearby space: hidden within it are more than 800,000 new stars. Their energetic activity blows holes in the clouds surrounding them, giving the nebula its lace-like structure.



97 Cartwheel Galaxy

This spiral galaxy suffered a head-on collision that created rings of star formation that rippled out from the centre. Ultraviolet and X-ray light released by new stars and violent black holes are visible in this image as purple and blue, while the green visible light shows the spokes of the cartwheel, revealing clues about the galaxy's shape before the impact.



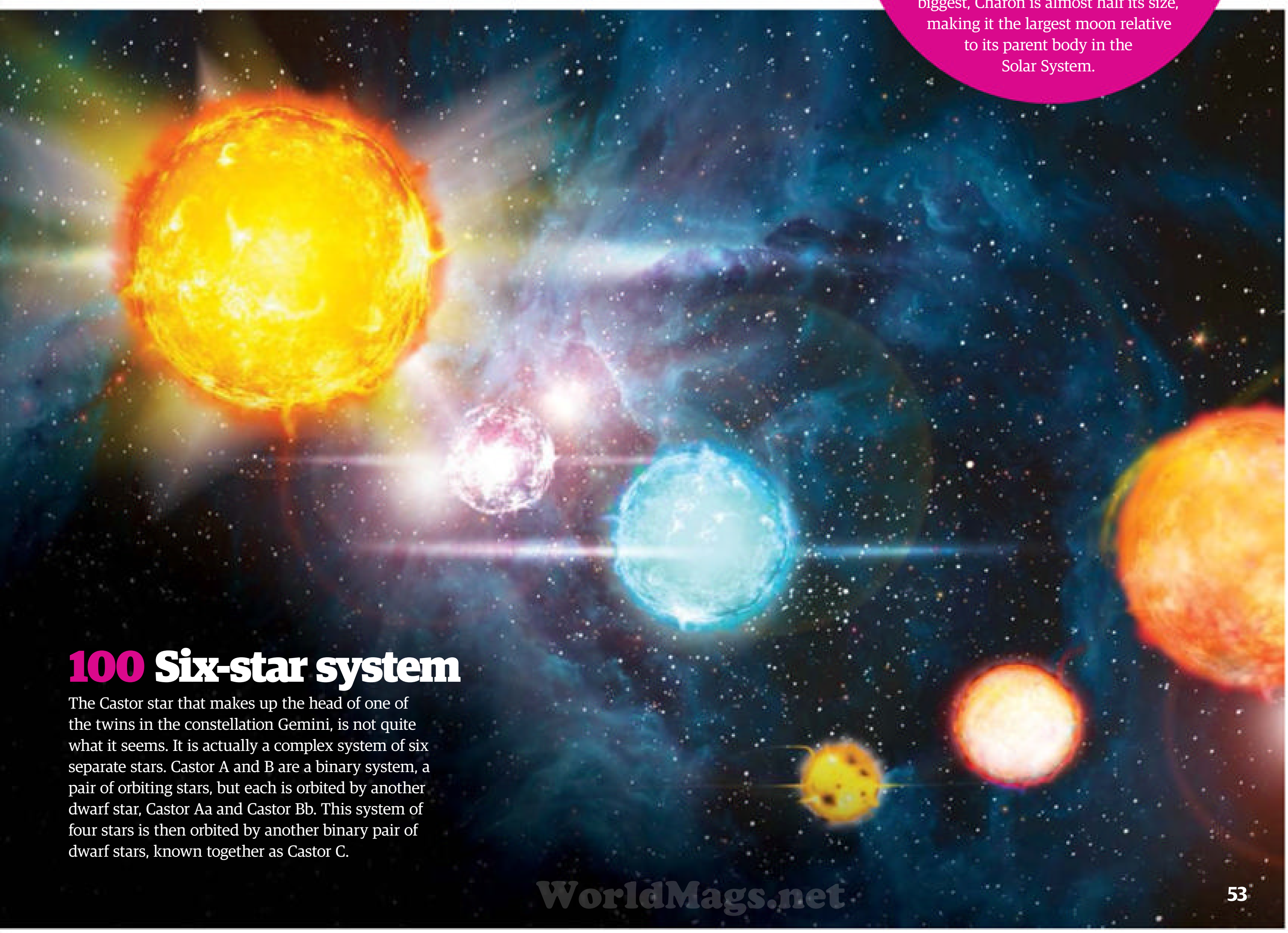


98 Jewel box

The NGC 3603 nebula is home to one of the most massive clusters of young stars in the Milky Way. Just 20,000 light years from Earth, the open cluster is described by NASA as a 'stellar jewel box', with three truly massive Wolf-Rayet stars nestled at its core. The hot young stars have blown away their blanket of dust and are blasting the surrounding hydrogen gas with ultraviolet light, illuminating the clouds.

99 Giant Moon

Long thought of as the ninth planet, Pluto was demoted to 'dwarf planet' in 2006. However, despite its diminutive size, Pluto is still a wonder in its own right. The tiny ball of rock and ice would fit inside the United States, but it manages to hold on to five moons. The biggest, Charon is almost half its size, making it the largest moon relative to its parent body in the Solar System.



100 Six-star system

The Castor star that makes up the head of one of the twins in the constellation Gemini, is not quite what it seems. It is actually a complex system of six separate stars. Castor A and B are a binary system, a pair of orbiting stars, but each is orbited by another dwarf star, Castor Aa and Castor Bb. This system of four stars is then orbited by another binary pair of dwarf stars, known together as Castor C.

EDGE of the

UNIVERSE

What strange and familiar phenomena can we see at the limit of our most powerful telescopes?

In December 1995 astronomers using the Hubble Space Telescope began a remarkable experiment. Turning the telescope's powerful gaze on an apparently empty patch of sky in the constellation Ursa Major, they let its cameras soak up rare photons of light for more than 100 hours. The resulting image revealed countless galaxies disappearing into the darkness – it would prove to be the first of several *Hubble Deep Field* images. These awe-inspiring pictures have revealed the remote universe in ever-increasing detail.

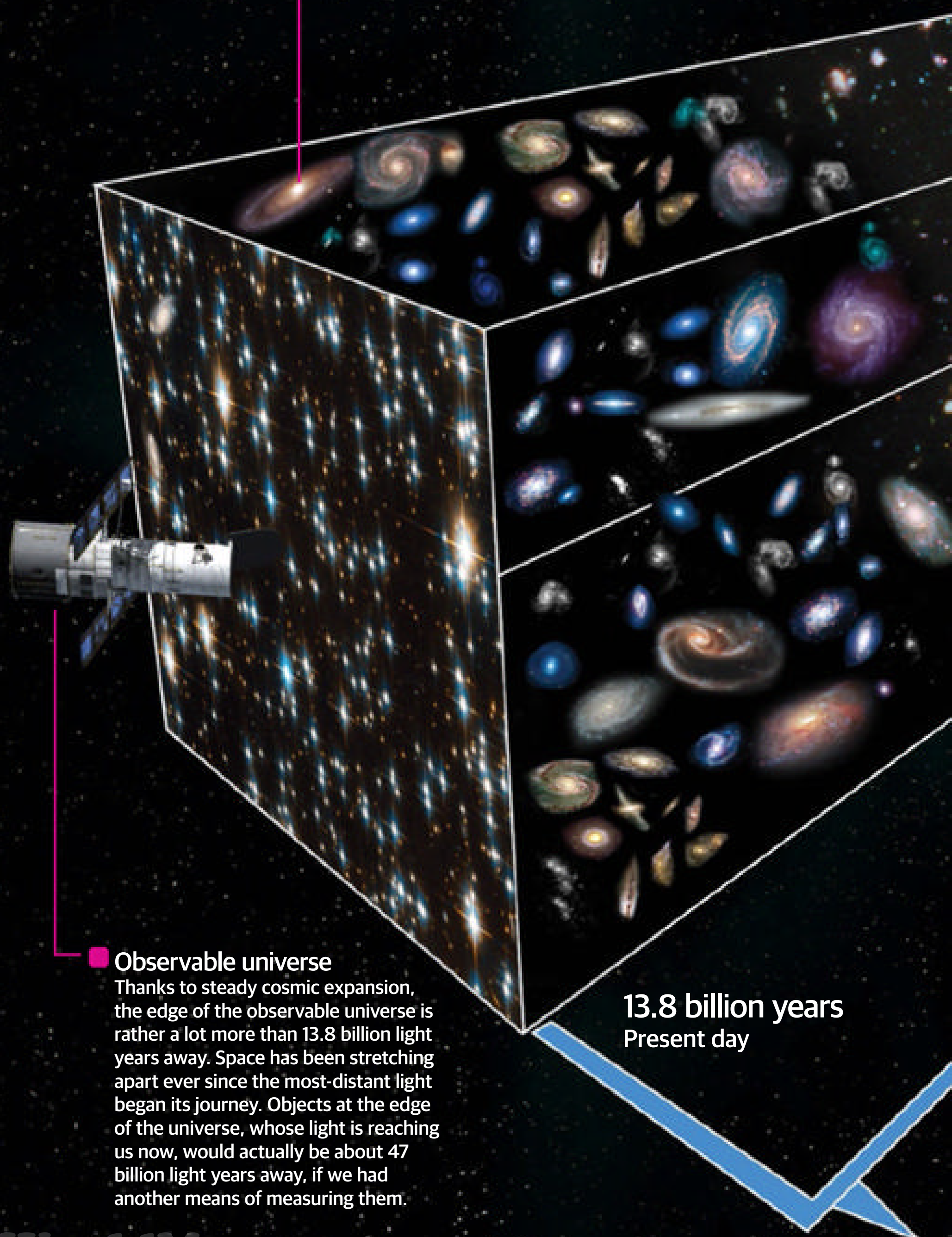
From our location on Earth, the entire cosmos is an enormous time machine – light might be the fastest thing there is, but even its tremendous top speed of 300,000 kilometres (186,400 miles) per second dwindles in comparison with the vast distances of remote stars and galaxies. Everywhere we look in distant space, we're also looking back in time and the more powerful our telescopes get, the further back we can see.

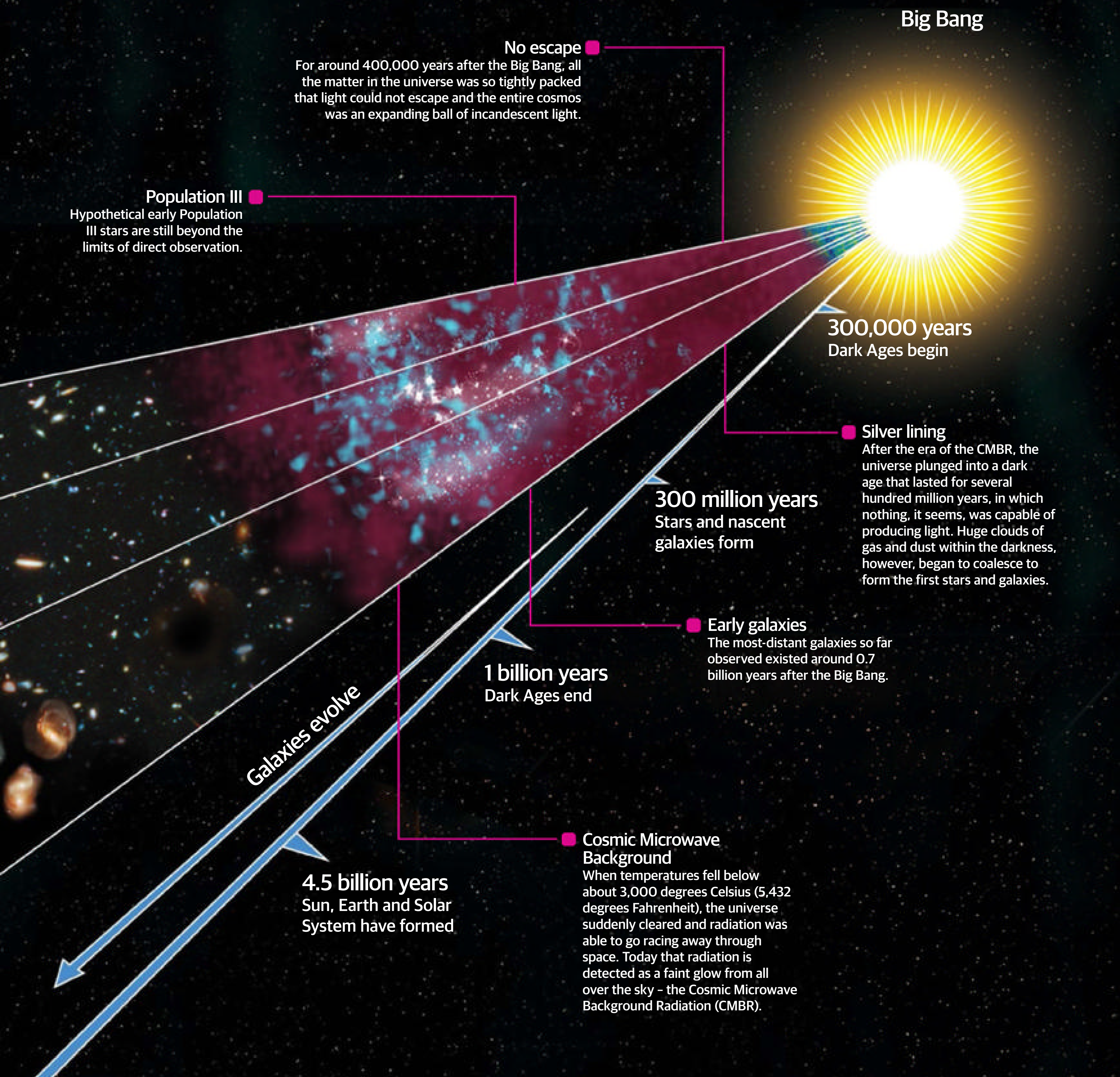
With larger telescopes and ever-increasing exposures, we might expect to go on seeing more and more galaxies stretching on forever – but the physics of the cosmos put a limit on our ambitions. Overwhelming evidence suggests the universe was born in the Big Bang some 13.8 billion years ago and has been expanding ever since – no light could have started its journey before that time. So, from our point of view, Earth is at the centre of a bubble of expanding space and time that stretches out in every direction, to a boundary where light has only just had time to reach us – the so-called observable universe. Fortunately, most astronomers view the cosmic time machine not as a barrier but as a hugely informative tool, as Dr Daniel Mortlock of Imperial College London explains. "The reason people put so much effort into finding such distant objects isn't really because they're far away. Rather, it's because we see them as they were so long ago. As far as we can tell the universe is broadly the same wherever we look, so what these observations really do is help us understand how the universe was billions of years ago. In some ways, this sort of astronomy is rather like archaeology."

Searching for such distant objects is a huge challenge, as Professor Steve Finkelstein of the University of Texas, Austin, knows well: "These galaxies are incredibly distant, so no matter what we do, its going to take a long time to observe them. Even the brightest galaxies we can observe, less than a billion years from the Big Bang, are very faint. The faintest star your eye can see is an incredible 40 million times brighter than the brightest distant galaxy. That's why we need very large telescopes."

Cosmic expansion has another important affect on our view of distant objects – as space has stretched, it has also stretched the wavelengths of light rays travelling through it – the effect known as Doppler shift. "Due to the expanding universe, all of the ultraviolet and visible light from these galaxies are Doppler-shifted into the infrared," continues Professor Finkelstein. "While we can observe some of these wavelengths from the ground, the technology is in its infancy." What's more, Earth's own atmosphere glows at many infrared wavelengths, swamping out the faint rays from distant objects and obscuring them from observation.

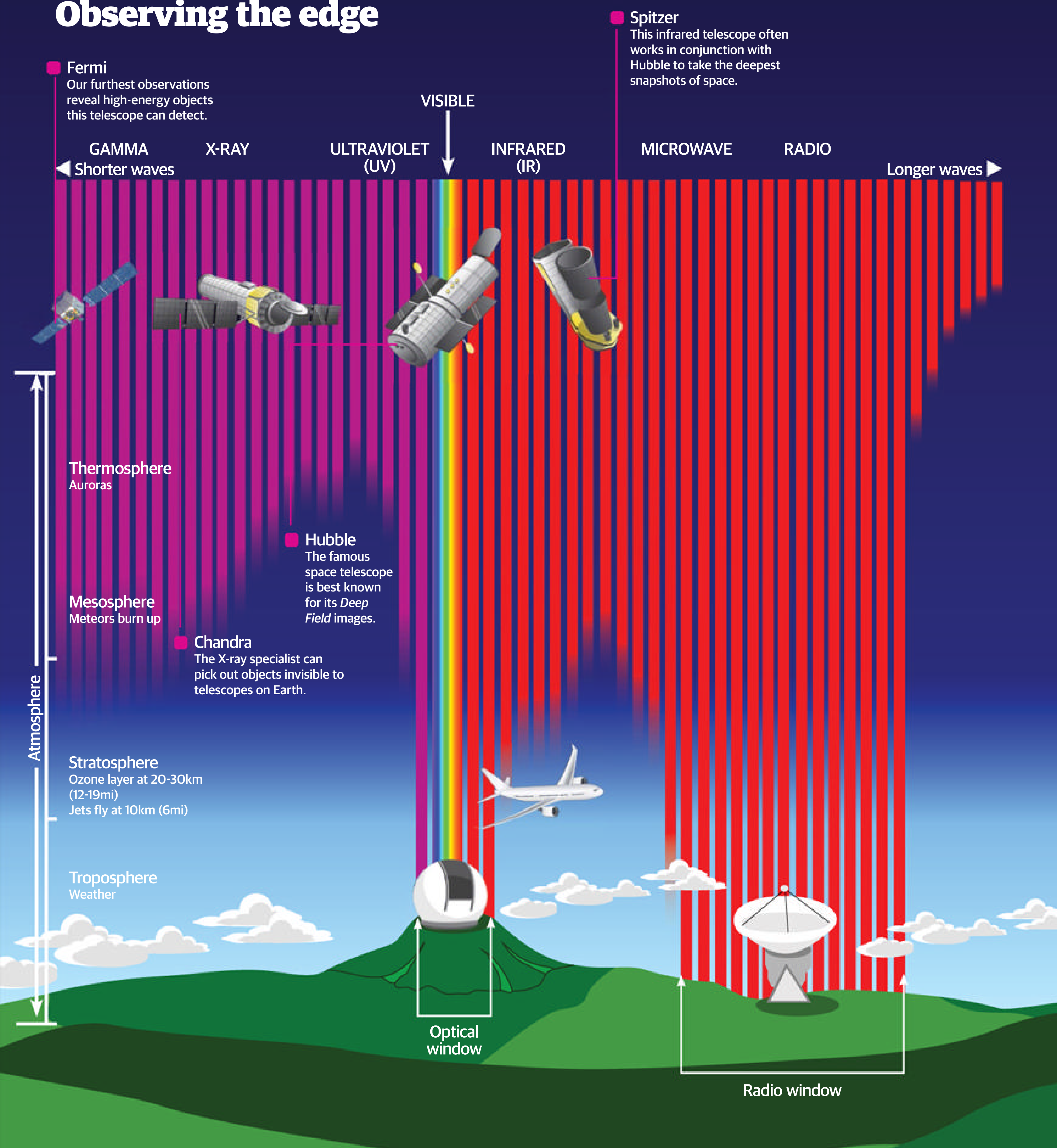
Towards the edge

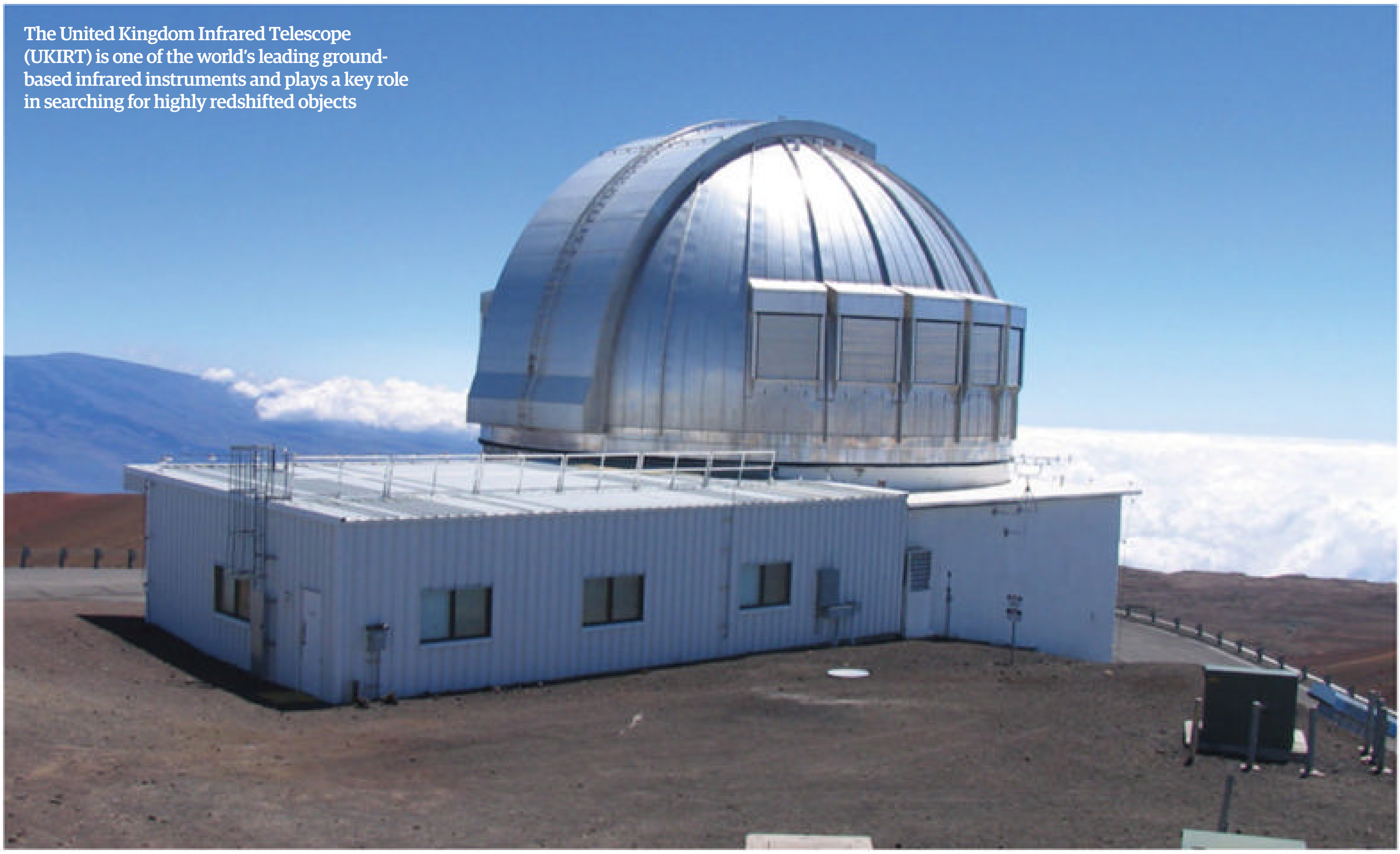




> "Even the brightest galaxies we can observe, less than a billion years from the Big Bang, are very faint"
>
> **Professor Steve Finkelstein, University of Texas**

Observing the edge





The United Kingdom Infrared Telescope (UKIRT) is one of the world's leading ground-based infrared instruments and plays a key role in searching for highly redshifted objects

The general shift of light from distant galaxies into redder, longer wavelengths is an important hint for astronomers hunting the earliest galaxies. Deep-red galaxies appear as blobs just a few pixels across in long-exposure Hubble images, but are often seen close to gravitational lenses. These are natural cosmic zoom lenses created when a massive galaxy cluster closer to Earth distorts and intensifies light from more-distant objects.

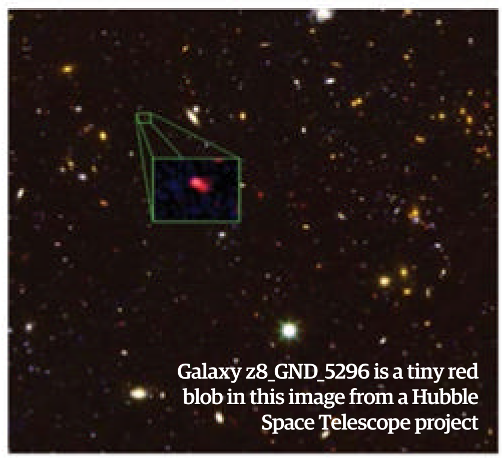
In 2013, Professor Finkelstein and his team discovered the most-distant galaxy yet identified, catalogued z8_GND_5296, as part of a special project using the infrared capabilities of the Hubble Space Telescope. "Spectral observations from Hawaii's enormous W.M. Keck Observatory soon confirmed an immense speed of retreat, plus a huge distance corresponding to an origin about 700 million years after the Big Bang," he explains. "But that wasn't all: when we used our observations to infer the physical properties of this galaxy, we found it was forming stars at an incredible rate. Galaxy z8_GND_5296 is turning an amount of gas equal to 300 times the mass of our Sun into new stars every year – that's a rate of around 150 times that of the Milky Way."

Researchers expected stars to form more quickly in such distant young galaxies, but z8_GND_5296 was still creating stars 30 times faster than anticipated. Finkelstein's team showed there are many similar galaxies in the early universe, "Simulations of the distant universe don't have such galaxies in them, so by observing them we're learning something incredibly new about the distant universe."

"If Population III stars exist, their light would be travelling from the very edge of the known universe"

While astronomers like Professor Finkelstein focus on looking for entire galaxies in the early universe, they're not the only possible targets for astronomers hoping to probe the very edge of the cosmos. For instance Dr Mortlock and his colleagues concentrate on the search for quasars. These are active galactic nuclei in which the giant central black hole is swallowing up material from its surroundings and heating it up in the process. This results in an intensely bright central region that may be up to hundreds of thousands of times brighter than its parent galaxy.

"This incredible luminosity is also the reason we can see quasars so far away," explains Dr Mortlock. "Even the most-distant quasar known, ULAS J1120+0641, which is seen as it was when the universe was just five per cent of its current age of 13.8 billion years, is a relatively bright astronomical source. It's approximately 10,000 times brighter than normal galaxies at a similar distance."



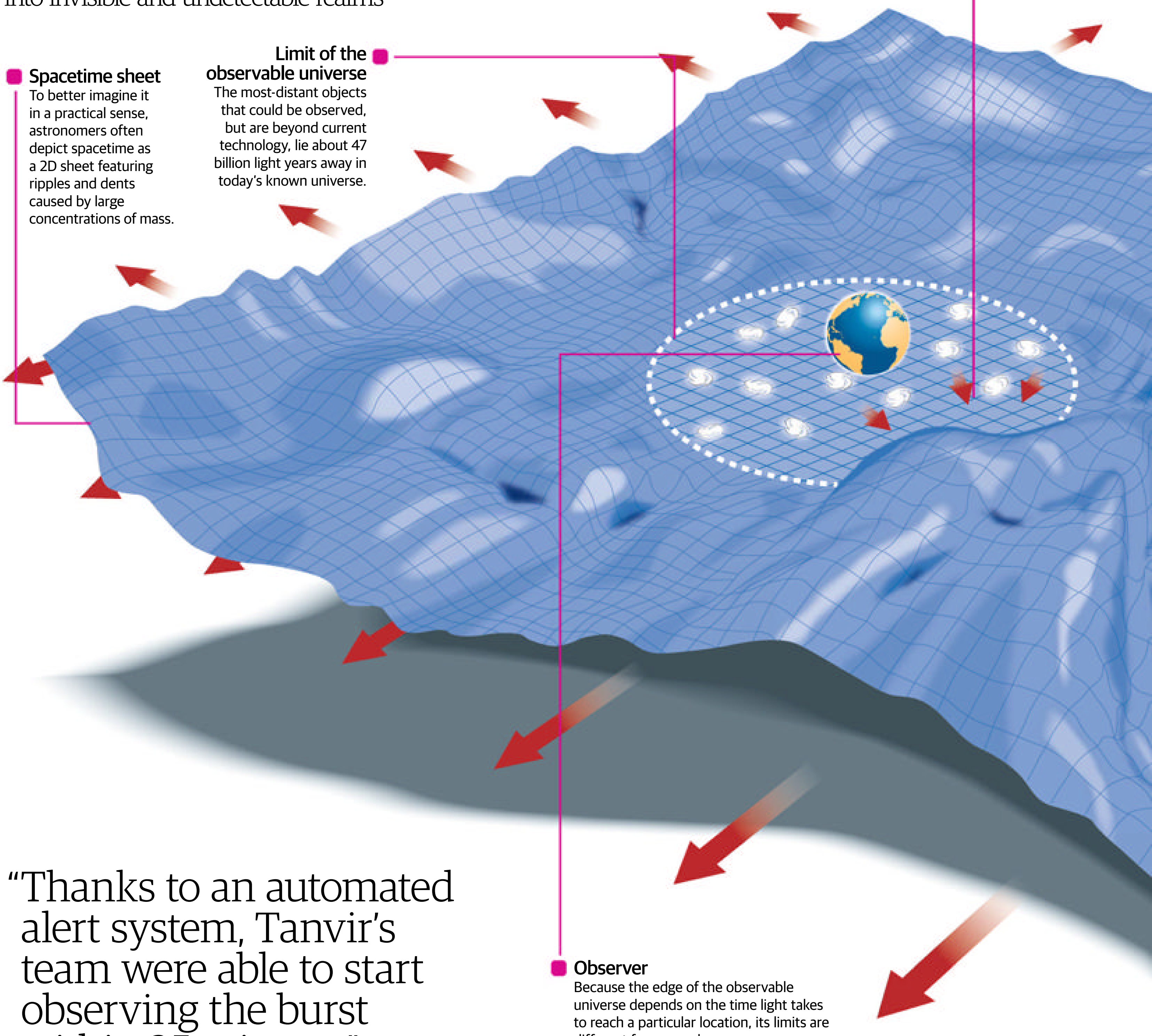
Galaxy z8_GND_5296 is a tiny red blob in this image from a Hubble Space Telescope project

Dr Mortlock's team identified the ULAS object as part of a near-infrared sky survey using the 3.8-metre (12.5-foot) United Kingdom Infrared Telescope (UKIRT) on Mauna Kea, Hawaii. "The universe has expanded by a factor of eight or so since the light we see from ULAS J1120+0641 was emitted, and the wavelength of this light has been stretched by the same amount. So, the ultraviolet light emitted from these quasars is now seen by us in the infrared part of the spectrum."

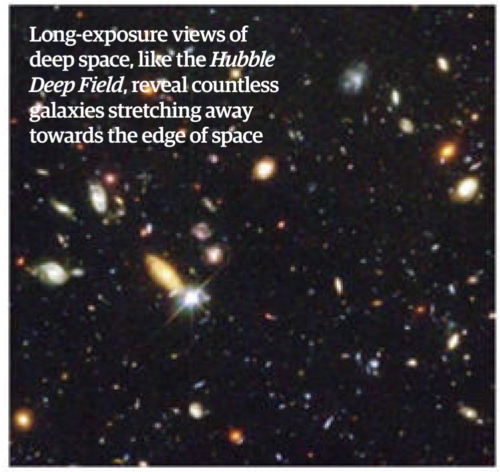
Surprisingly this distant object has turned out to closely resemble other, relatively nearby quasars: "It appears to have a very similar mix of elements and so broadly the same kind of spectrum. This makes it comparatively easy to determine the physical properties of this object and particularly the mass of

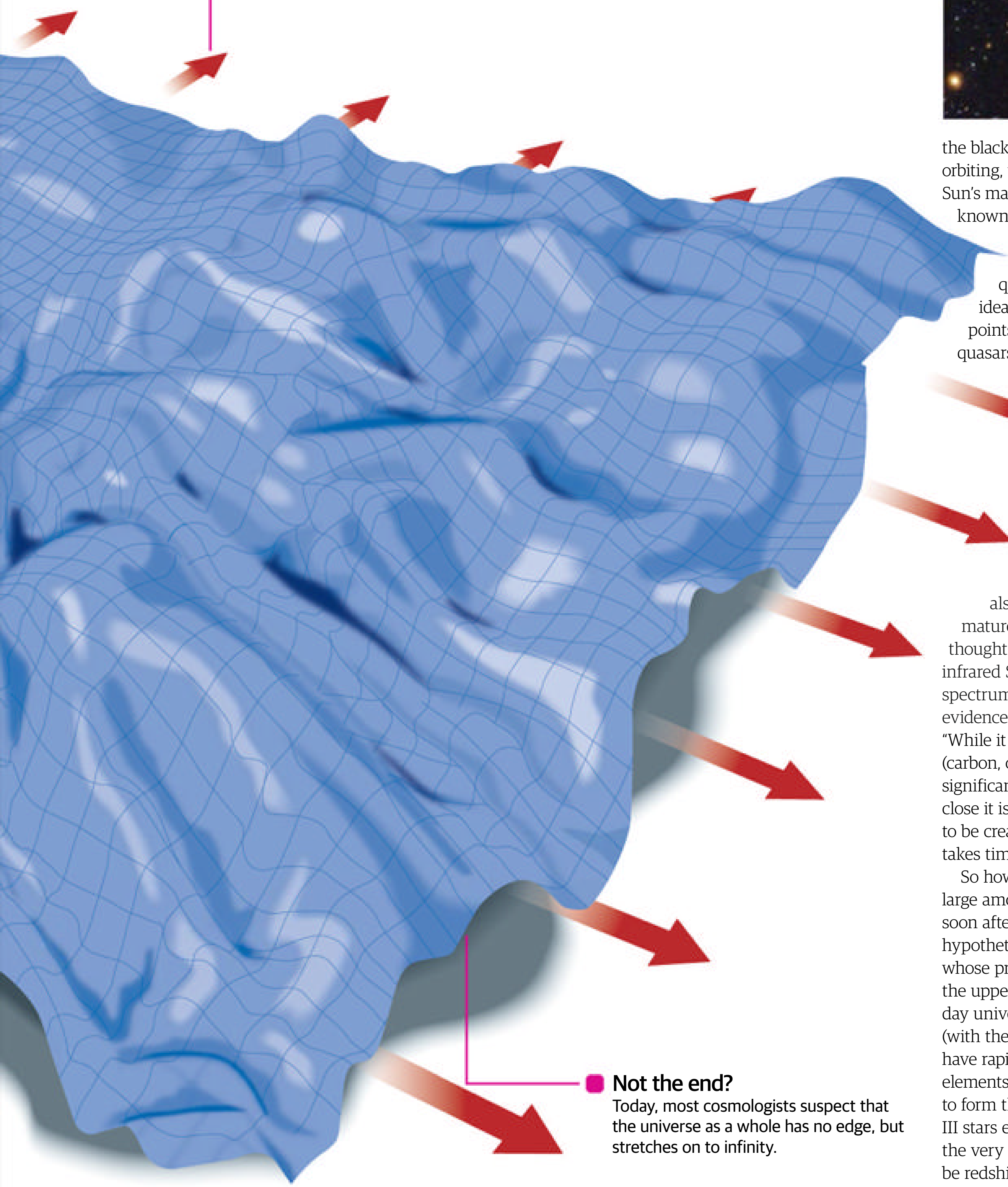
Beyond the edge

The observable cosmos might mark the edge of what we can see, but it's not the edge of everything – the universe stretches away far beyond what we can see, into invisible and undetectable realms



"Thanks to an automated alert system, Tanvir's team were able to start observing the burst within 25 minutes"


Long-exposure views of deep space, like the *Hubble Deep Field*, reveal countless galaxies stretching away towards the edge of space

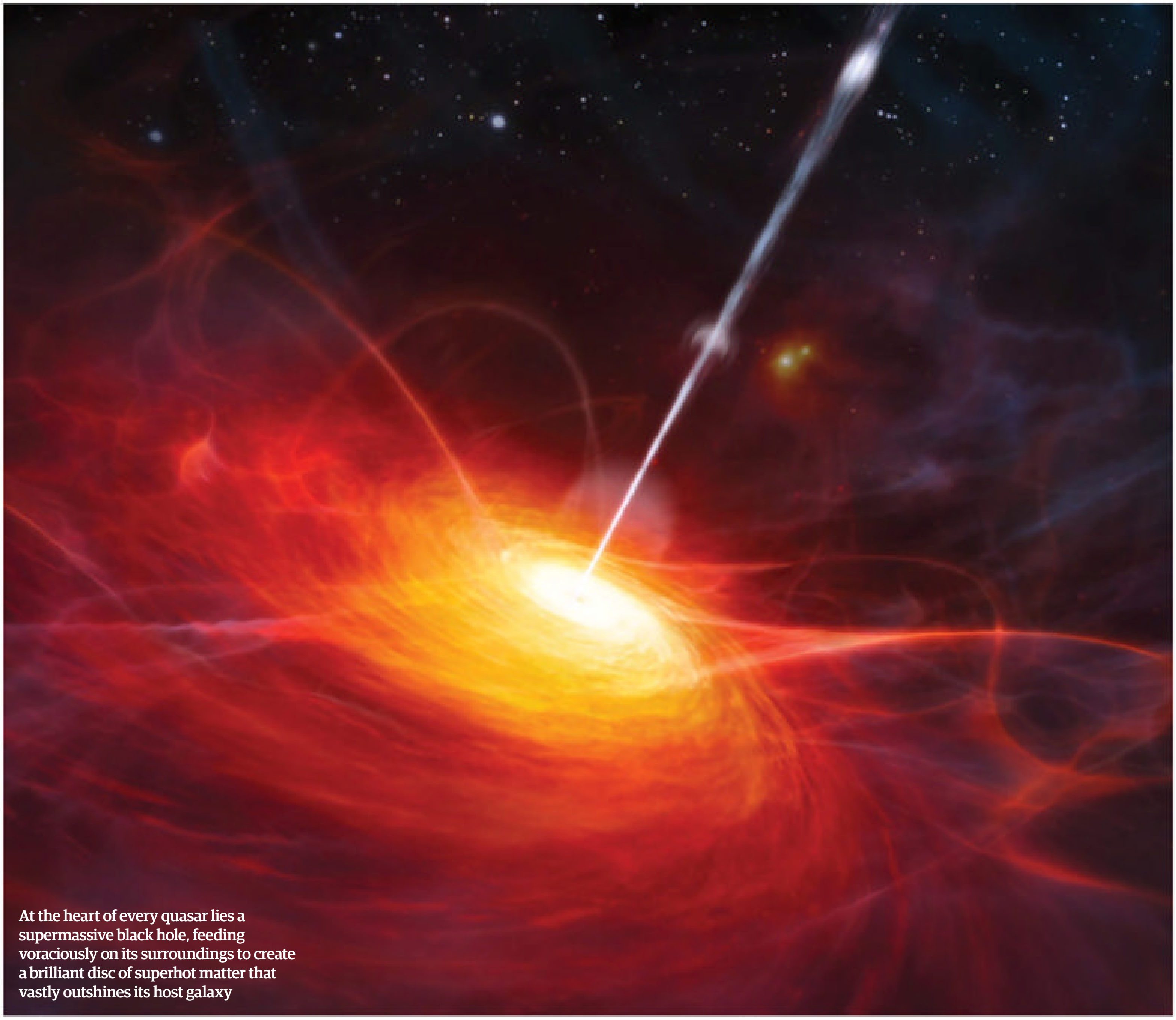


the black hole. From the speed at which the gas is orbiting, we estimate that it has 2 billion times the Sun's mass. This is not the most-massive black hole known, but it is the earliest supermassive black hole that has been found."

The discovery of objects like the ULAS quasar has some important implications for ideas about the early universe. Dr Mortlock points out: "The mere existence of distant quasars – and particularly the supermassive black holes that power them – is something of a conundrum. Simple models of black hole formation and growth suggest that such monsters shouldn't have formed so quickly. It's no surprise to see them billions of years after the Big Bang, but 0.8 billion years doesn't seem like enough time."

Intriguingly, galaxies like z8_GND_5296 also seem to suggest an early universe that matured much more quickly than previously thought. Professor Finkelstein's team used the infrared Spitzer Space Telescope to measure the spectrum of their record-breaking galaxy, discovering evidence for surprisingly large amounts of oxygen. "While it doesn't contain as many heavy elements (carbon, oxygen, iron) as our own, there are still significant amounts. This is surprising given how close it is to the Big Bang, since heavy elements had to be created in early generations of stars and that takes time."

So how could supermassive black holes and large amounts of heavy elements have formed so soon after the Big Bang? An answer might lie in a hypothetical early generation of short-lived stars whose primitive composition enabled them to break the upper limits of stellar mass seen in the present-day universe. These so-called Population III stars (with the mass of a thousand Suns or more) could have rapidly enriched the early universe with heavy elements, and also left-behind enormous black holes, to form the seeds of the first galaxies. If Population III stars exist, their light would be travelling from the very edge of the known universe and would be redshifted far more than even the most-distant known galaxies. As such, they're beyond the limits of current technology, but a prime target for NASA's James Webb Space Telescope (JWST), the enormous infrared observatory scheduled for launch in 2018.



At the heart of every quasar lies a supermassive black hole, feeding voraciously on its surroundings to create a brilliant disc of superhot matter that vastly outshines its host galaxy

Another significant class of objects at the edge of the known cosmos is perhaps the most elusive of all – the intense but short-lived bursts of short-wavelength electromagnetic energy known as gamma-ray bursts (GRBs). First discovered in the 1960s, they have been the subject of huge speculation amongst experts for several decades. "The luminous output is the equivalent of capturing the Sun's entire light output for its 10-billion-year lifetime as an ordinary star, saving it all up in a bottle, then releasing it in a single 30-second blast of light," explains Professor Derek Fox of Penn State University.

GRBs seem to fall into several distinct categories based on the strength and duration of their bursts. One major group, the so-called long-duration GRBs (for which the gamma-ray flash is longer than about two seconds) are thought to be produced during the deaths of massive stars.

Nial Tanvir of the University of Leicester explains further: "It seems that when some stars (perhaps those about 30 to 40 times the mass of the Sun) run out of fuel and end their lives, they collapse due to gravity. In the process of doing this they eject an extraordinarily powerful jet of plasma. It's thought this energy is ultimately converted into electromagnetic radiation, particularly energetic gamma rays, but also lower-energy light (X-rays, optical, infrared, radio). If the jet is pointing towards us, this results in an extremely bright initial flash followed by a fading afterglow."

Professors Tanvir and Fox have identified some of the most-distant GRBs so far detected, responding to rays initially detected by NASA's Swift Gamma-Ray Burst mission. "Satellites like Swift communicate new discoveries automatically to the ground, where the information is forwarded to observers around the world on a timescale of a few tens of seconds. From this point we have to decide quickly how interesting any given burst appears to be, and what telescopes might be able to make rapid observations," explains Professor Tanvir.

The most-distant confirmed burst is known as GRB 090423 – a designation that indicates its date of discovery on 23 April 2009. Thanks to an automated alert system, Tanvir's team were able to start observing the burst within 25 minutes, using the UKIRT. Fox's team soon added their own observations from the observatory's bigger neighbour, the 8.2-metre (27-foot) Gemini North Telescope. "For the furthest gamma-ray bursts, one doesn't get much clue about their distance from the gamma-ray data, so it's critical to make optical and infrared observations of the afterglow as soon as possible, preferably within an hour or so."

"Right now, these borderlands may resemble an old seafarer's map, filled with mysterious monsterous beings"

So, why optical and infrared? Professor Tanvir elaborates: "Neutral hydrogen, which is plentiful in the universe, is very effective at absorbing ultraviolet light. For very distant explosions, the cosmological redshift moves this wavelength all the way through the optical and into the infrared. Hence the signature of a distant GRB is that it's invisible in the optical but visible in the infrared. The step between visibility and invisibility is what gives us the redshift. In this case, we finally pinned down the [exact redshift value], corresponding to a distance of about 13.1 billion light years. In other words, GRB 090423 was a star exploding only about 630 million years after the Big Bang itself."

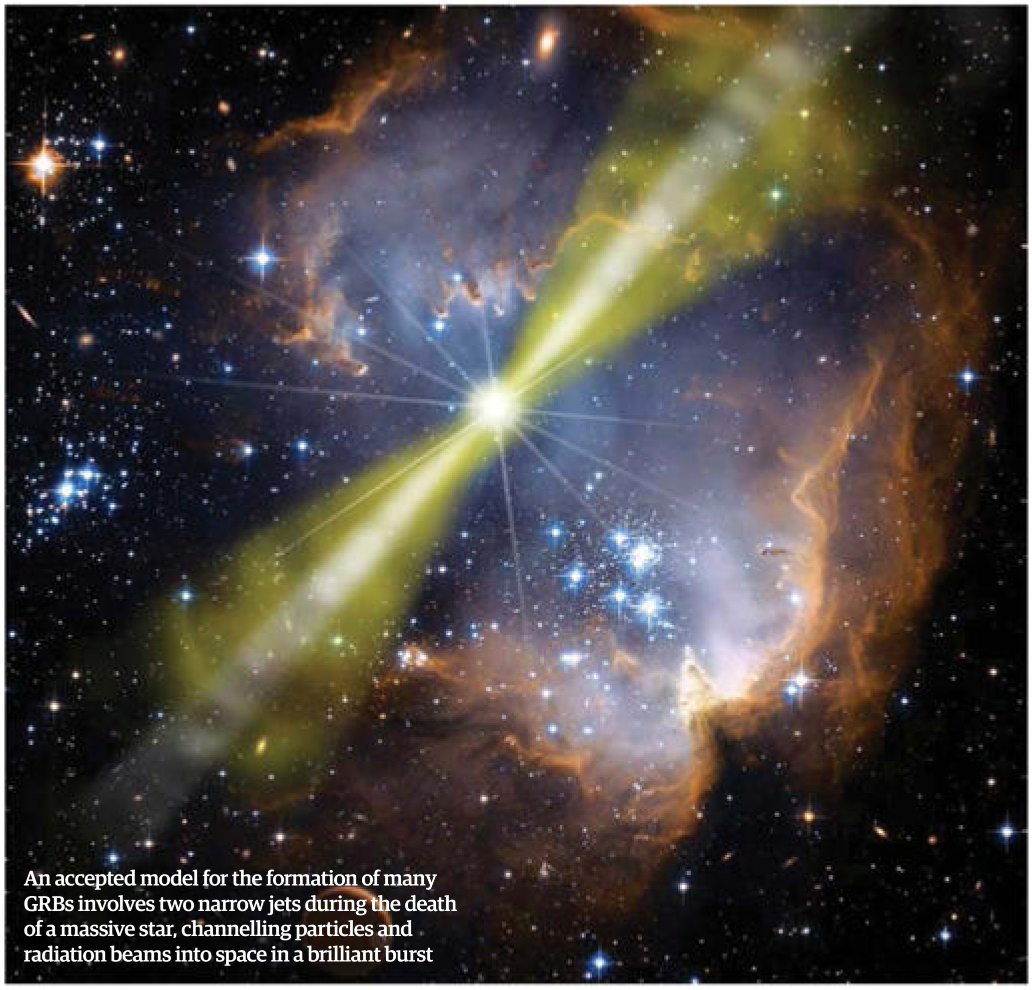
Remarkably, this record-breaking burst may even have been bettered just a few days later by another one, GRB 090429B. "The burst arrived at 1:30am," recalls Professor Fox. "My team was in charge of GRB work with the Gemini North telescope on Mauna Kea that night – we quickly saw that Swift had found an X-ray afterglow, but saw no optical or UV emission, so that meant we probably wanted to observe in the red and near-infrared bands to see if we had a high-redshift burst.

"Working with Professor Nial Tanvir and his colleagues, we found a relatively bright near-infrared afterglow with no optical light – bingo! The next night we requested further imaging and used it to confirm the fading of the source we had seen," Professor Fox continues. "That was the burst afterglow for certain, but sadly we were never able to get its spectrum."

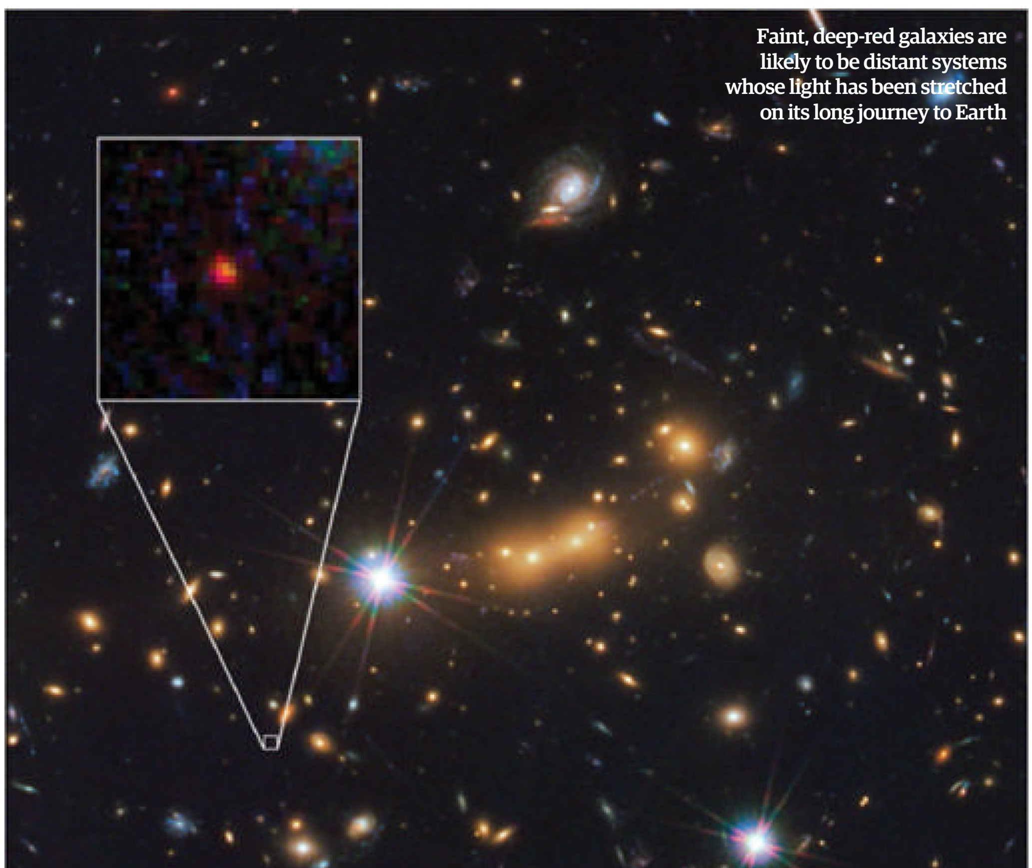
As a result, estimates of GRB 090429B's distance remain frustratingly imprecise, but the best estimates give it an even greater redshift value. This suggests that it may have exploded around 100 million years earlier than GRB 090423.

"Even limited information potentially has important consequences. For instance, the fact that none of the GRB host galaxies at [similar redshift values] has been detected by Hubble so far, suggesting that the large majority of this early star formation is happening in galaxies that are too small and faint for even Hubble to see."

The next few years surely promise to be an exciting time for researchers probing the edge of the observable universe. At the moment, these borderlands may resemble an old seafarer's map, filled with mysterious monsters we are only just beginning to understand. But the launch of the JWST will help bring the early galaxies and perhaps even the very first Population III stars into focus, giving us an unprecedented view both out into the depths of space and an essential glimpse back to the very beginnings of the cosmos. ■



An accepted model for the formation of many GRBs involves two narrow jets during the death of a massive star, channelling particles and radiation beams into space in a brilliant burst



Faint, deep-red galaxies are likely to be distant systems whose light has been stretched on its long journey to Earth

10 BIGGEST THINGS IN SPACE

Walk with us across the staggering enormity of space and witness gigantic asteroids through to mammoth stars, sprawling galaxies and the biggest thing in the cosmos…

The biggest thing in space that we're sure of is the biggest thing we can see, which is the cosmic web of the observable universe, the three-dimensional scaffold of galactic structures that makes up what our best instruments are able to observe. A more precise estimate of just how big this is was recently returned by the ongoing Planck space mission, which aims to provide a complete map of the sky. By mapping the cosmic microwave background, the afterglow left over from the Big Bang, scientists have determined that the furthest objects we can observe from Earth are around 13.8 billion light years away. So how far beyond that does the universe extend?

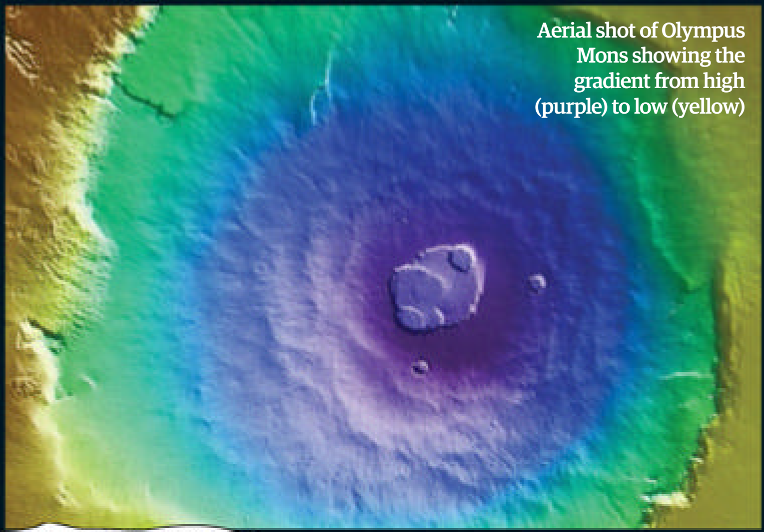
The truth becomes muddied when you approach the boundary of what we can see and talk about the size of the actual universe. General scientific consensus puts the distance between either end of the universe at 93 billion light years. But the problem is, because it has been expanding since the Big Bang and because of the finite speed of light, we cannot see the light from objects beyond a certain point. Some scientists put the size of the universe at an astonishing 100,000 trillion times what we can see, while others say the universe is actually smaller than the observable universe and the light from the most distant galaxies has wrapped around to create duplicates of nearer galaxies that appear far away.

Within the known observable upper limit of our celestial sphere though, there are many objects whose size we can put a definite figure on, which are still enormous enough to send the mind reeling when juxtaposed with the planets, stars and even galaxies we can more easily relate to. These are ten of the biggest recorded things in space.

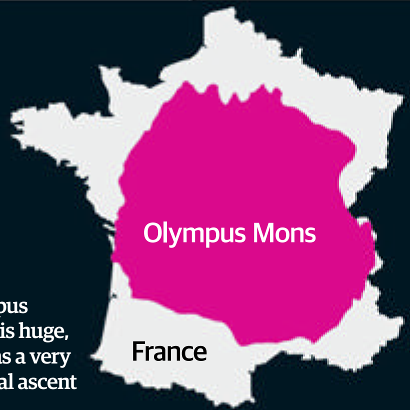
BIGGEST VOLCANO Olympus Mons

Let's start small – relatively – with the biggest volcano in the Solar System. Olympus Mons can be found in the Tharsis Montes region of Mars and rises to a peak of 25 kilometres (16 miles) high and 624 kilometres (374 miles) wide with an 80-kilometre (50-mile) wide caldera. It towers over even the tallest mountains on Earth, Everest at 8.8 kilometres (5.5 miles) and Mauna Kea (which is 10 kilometres/6.2 miles if measured from the ocean floor), while dwarfing our biggest volcanoes with around 100 times more volume than Hawaii's Mauna Loa.

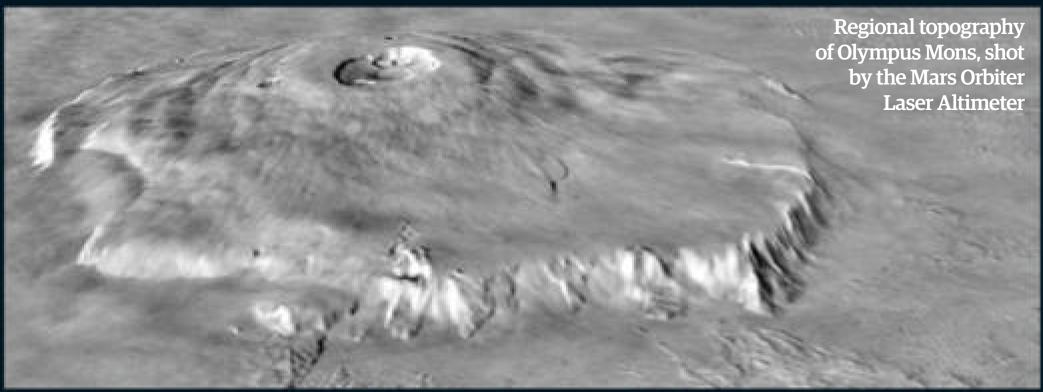
The volcanic Tharsis Montes region of Mars is actually home to several of the biggest volcanoes in the Solar System, including Ascraeus Mons and Elysium Mons, which are 14.9 kilometres (9.3 miles) and 12.6 kilometres (7.8 miles) high respectively. The reason why Mars is a great breeding ground for super-sized volcanoes is down to its geology and its gravity. On Earth, the tectonic plates are continuously moving over and under each other on top of the mantle, so that the lava is distributed over a wide area between many volcanoes instead of just one. On Mars, the crust doesn't move in the same way, so the lava just piles up in the same spot. Because of the lower Martian gravity and higher rates of eruption, the lava flows are much longer, too.



Aerial shot of Olympus Mons showing the gradient from high (purple) to low (yellow)

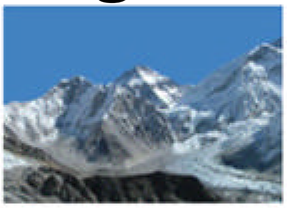


Olympus Mons is huge, but has a very gradual ascent



Regional topography of Olympus Mons, shot by the Mars Orbiter Laser Altimeter

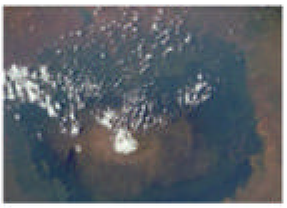
5 highest summits on Earth (by continent)



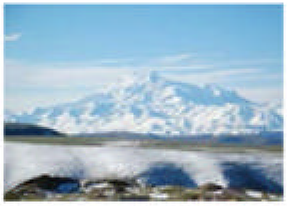
Mount Everest (8,848m/29,029ft)
Earth's highest mountain is part of the towering Asian range, the Himalayas.

Aconcagua (6,960m/22,837ft)
The highest mountain of the Americas is nearly a clear kilometre shorter than Everest.

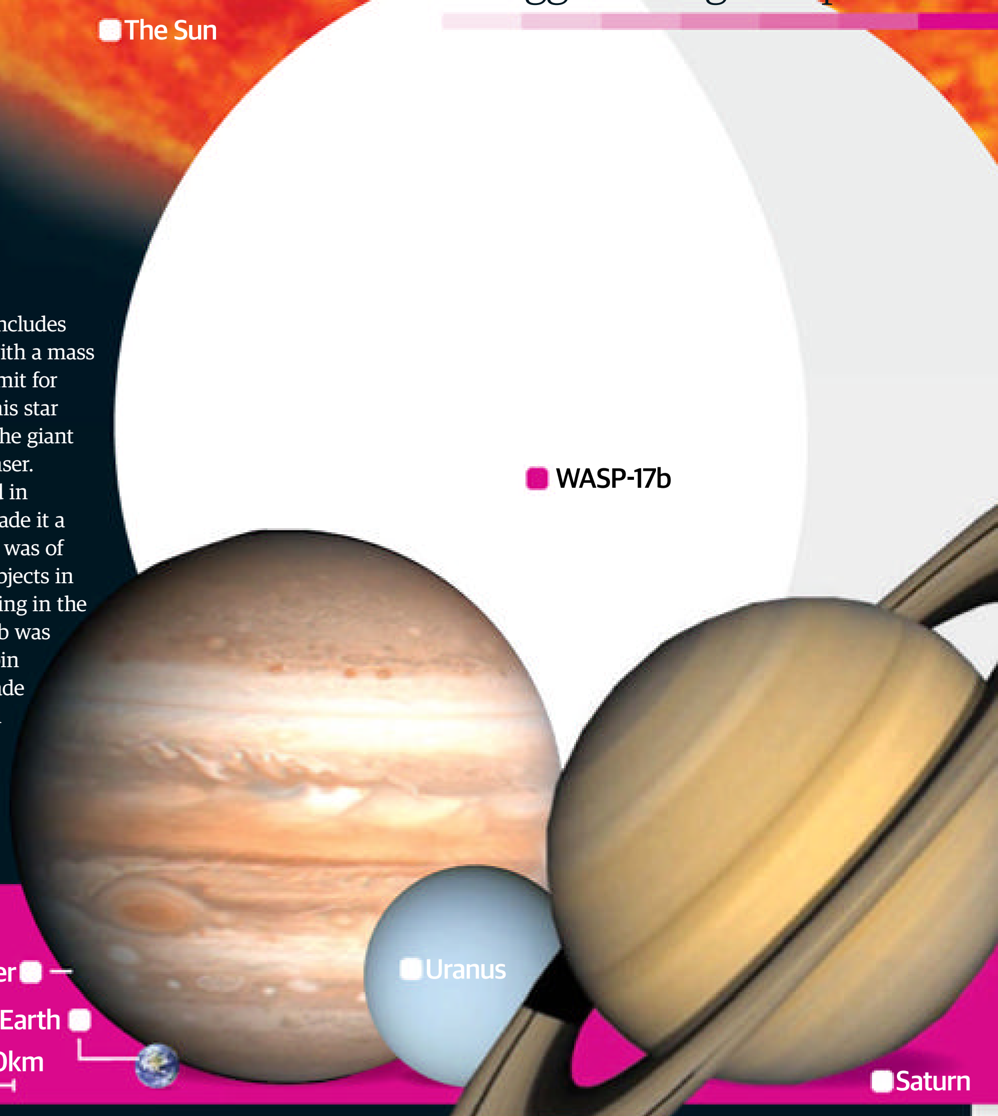
Mount McKinley (6,194m/20,320ft)
North America's McKinley has the largest base to peak rise of any mountain above sea level.



Kilimanjaro (5,895m/19,341ft)
This African peak is composed of three volcanoes, two extinct and one dormant.



Mount Elbrus (5,642m/18,510ft)
The Caucasus range boasts Russia's highest mountain – another dormant volcano.



BIGGEST PLANET WASP-17b

WASP-17b is a huge planet, twice the size of Jupiter that orbits a yellow-white dwarf star similar to the Sun, around 1,000 light years from Earth. It's considered a 'hot Jupiter' due to the extreme proximity of its orbit with its parent star. It has a density around half that of Jupiter and has one of the lowest known densities of all the planets. It's a combination of the baking heat it endures as well as the tidal forces of its nearby host star's gravity, which is suspected to have caused WASP-17b to inflate to its enormous size and low density.

WASP-17b has an estimated equatorial radius of just over 136,000 kilometres (84,500 miles), which makes it bigger than some small main-sequence stars. This includes OGLE-TR-122B, a tiny star with a mass that borders on the lower limit for hydrogen fusion in stars. This star is just over half the size of the giant exoplanet, but 50 times denser.

WASP-17b was discovered in 2009 and though its size made it a compelling subject, its orbit was of even more interest. Other objects in the same system were orbiting in the right direction but WASP-17b was travelling contrary to the spin of its host star. This retrograde orbit may have been caused by a close encounter with another object that caused the planet to slingshot in the opposite direction.

BIGGEST ASTEROID Pallas

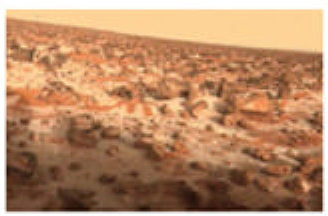

An ultraviolet image of Pallas taken by Hubble

Of course, like the biggest mountain, the size of asteroids and the limitation of current observational technology mean that the biggest asteroids we know of are restricted to those in our own Solar System. There's also a technicality in their definition: with a diameter of 950 kilometres (590 miles) and containing around one third of the total mass of the asteroid belt, Ceres used to be the biggest asteroid but was upgraded to 'dwarf planet' in 2006, handing fellow asteroid belt object Pallas the accolade of biggest known asteroid by default.

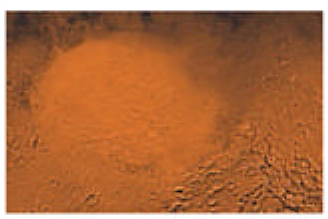
However, with an average diameter of 544 kilometres (338 miles) it's still a whopper. Its closest contender for the top spot is Vesta, which has less volume but greater mass than Pallas. Between them, they make up around 16 per cent of the total mass of the asteroid belt and along with several other big asteroids, they were once believed to be part of a much larger 'missing' planet that was thought to orbit the space between Mars and Jupiter before being destroyed. That theory has since been debunked and it's now known that Ceres, Pallas and their companions, along with the rest of the asteroid belt are the vestiges of a protoplanetary disc that was perturbed by the gravity of Jupiter and failed to accrete into a planet.

Pallas would easily fill the Vredefort crater in South Africa, the largest impact crater on Earth (at around 300 kilometres/186 miles in diameter), and is more than 30 times bigger than the meteorite that created the Sudbury Basin in Canada over 1.8 billion years ago. It's 100 times bigger than asteroid 1998 QE2 that flew by Earth in March 2013, which could have caused wide devastation if it had impacted.

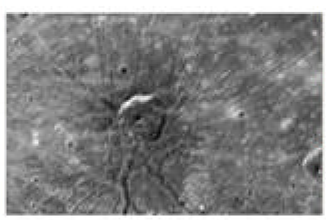
3 biggest craters in the Solar System



Utopia Planitia (3,300km/2,100mi)
Mars's blasted topography not only claims the tallest peak, but the widest confirmed impact crater in the Solar System. Considering Mars's proximity to the asteroid belt, it's not surprising this crater should be found here.



Hellas Planitia (2,300km/1,400mi)
Found in the southern hemisphere of Mars, this massive impact structure is the largest visible crater known in the Solar System. A detailed composite image of Hellas Panitia was taken by the Viking orbiters during their missions in the mid-Seventies.



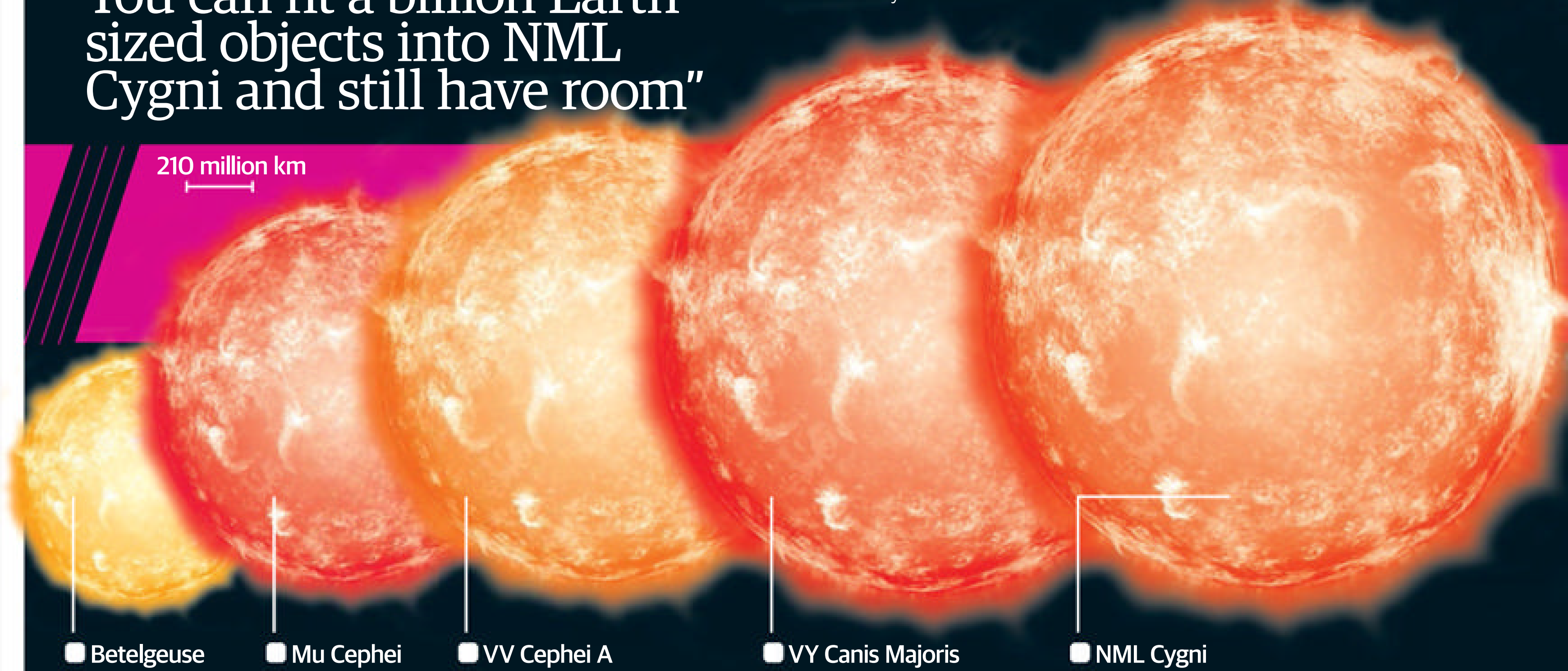
Caloris Basin (1,550km/960mi)
The baking surface of Mercury plays host to the third largest known impact crater in the Solar System. Caloris Basin is surrounded by a ring of mountains 2km (1.2mi) tall and material ejected up to 1,000km (620mi) around it.

BIGGEST STAR NML Cygni

We're moving into the realms of the true giants when we start to look at the biggest stars in the universe. Unlike planets, asteroids and other celestial objects that are too dark and too small to give away obvious clues to their presence from afar, these colossal balls of fusing hydrogen can bloom up to spheres so big that they're difficult to comprehend, blazing multi-spectra radiation across interstellar space and making their exact location known by the massive gravitational influence they have over their local environment.

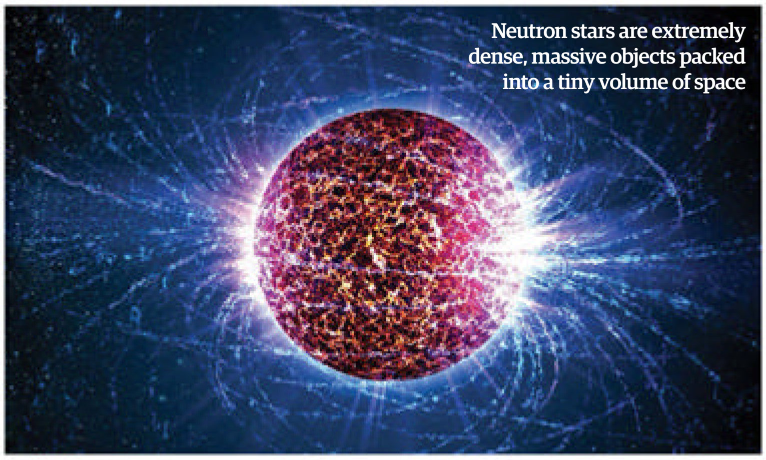
There are an estimated 100 to 400 billion stars in the Milky Way alone and because many are fairly easy to spot, we've been able to observe some serious contenders for the 'biggest star' accolade. VY Canis Majoris is huge beyond belief: this monster of a star is so big it would make our Sun seem like a pin-prick next to it. Found 5,000 light years from Earth, it has a radius of 1,420 times that of the Sun and was once thought to defy theory on the size and luminosity of stellar objects. However, since 2009 an even bigger star has been discovered. With a diameter of around 2.3 billion kilometres (1.4 billion miles), 400 million kilometres (250 million miles) wider than VY Canis Majoris, NML Cygni is a true intergalactic heavyweight. Placed at the centre of our Solar System, this stellar giant would swallow up the entire inner Solar System, including the asteroid belt, Jupiter and over half the distance between Jupiter and Saturn. You can fit a billion Earth-sized objects into NML Cygni and still have room left over. In terms of mass, too, it's pretty hefty, weighing in at 50 times that of the Sun, more than enough to create a huge supernova at the end of its life cycle. For the most massive star though, we have to look to the Wolf-Rayet star R136a1. It's found in a cluster of massive stars called R136, 165,000 light years away from Earth in the Large Magellanic Cloud. At a 'mere' 30 times the size of the Sun it's no NML Cygni, but it has 265 solar masses and is a million times brighter than the Sun: if placed in the Solar System it would outshine the Sun by as much as the Sun outshines the Moon. R136a1 is thought to have been even more massive too, as much as 320 solar masses but has lost a significant portion of this since its birth. But if we're talking about galactic-scale masses, it's the objects that are sometimes left behind in the death throes of massive stars that steal the show.

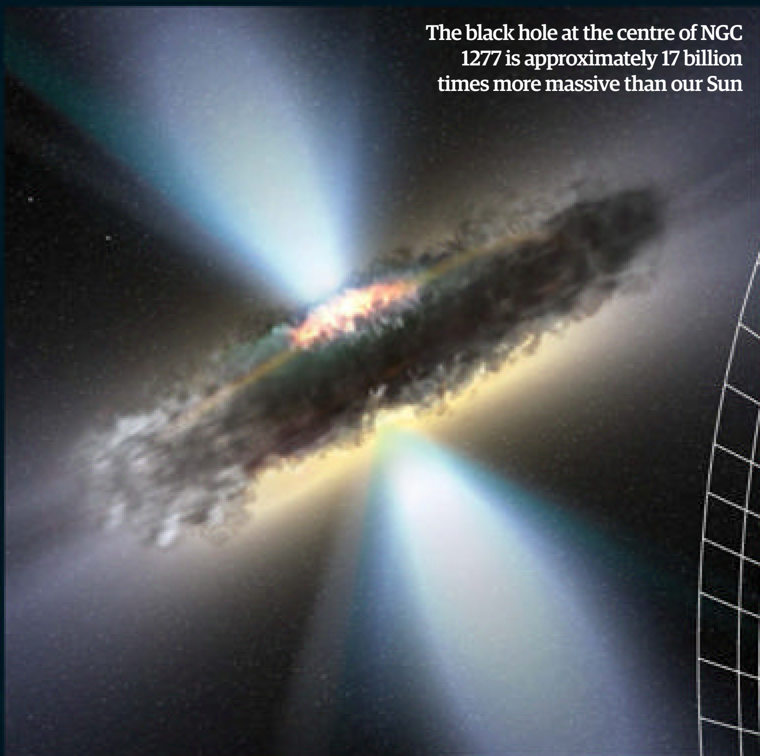
> "You can fit a billion Earth-sized objects into NML Cygni and still have room"



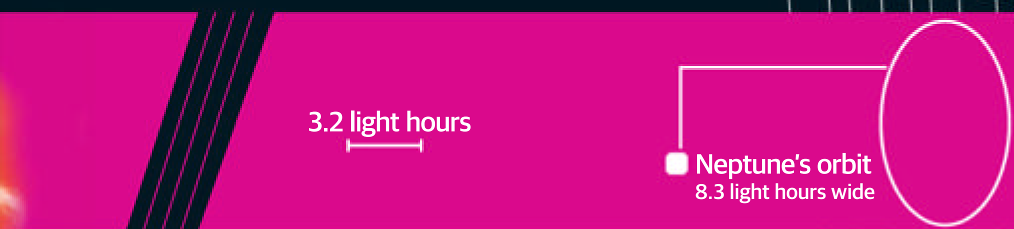
Size versus mass 101

It can be easy to get confused when scientists talk about the size of an object and its mass. Enormous celestial objects like stars and black holes in particular are said to be so-many solar masses, while their physical dimensions often aren't referred to. While weight is relative, mass is a fundamental property of everything and is a measure of its total matter, which only changes in exceptional physical circumstances. Large mass doesn't necessarily mean enormous size, though, depending on its density. For example, the biggest neutron star discovered (designated PSR J1614-2230) is nearly 200 trillion times denser than water, with twice the mass of the Sun packed into a space just 26 kilometres (16 miles) in diameter. Especially big, stellar-sized objects are described in terms of solar masses partly because stellar evolution is better understood this way. Sun-like stars tend to form red giants and then white dwarves at the end of their lives, while supergiants in the order of 20 solar masses form a black hole.


Neutron stars are extremely dense, massive objects packed into a tiny volume of space



The black hole at the centre of NGC 1277 is approximately 17 billion times more massive than our Sun

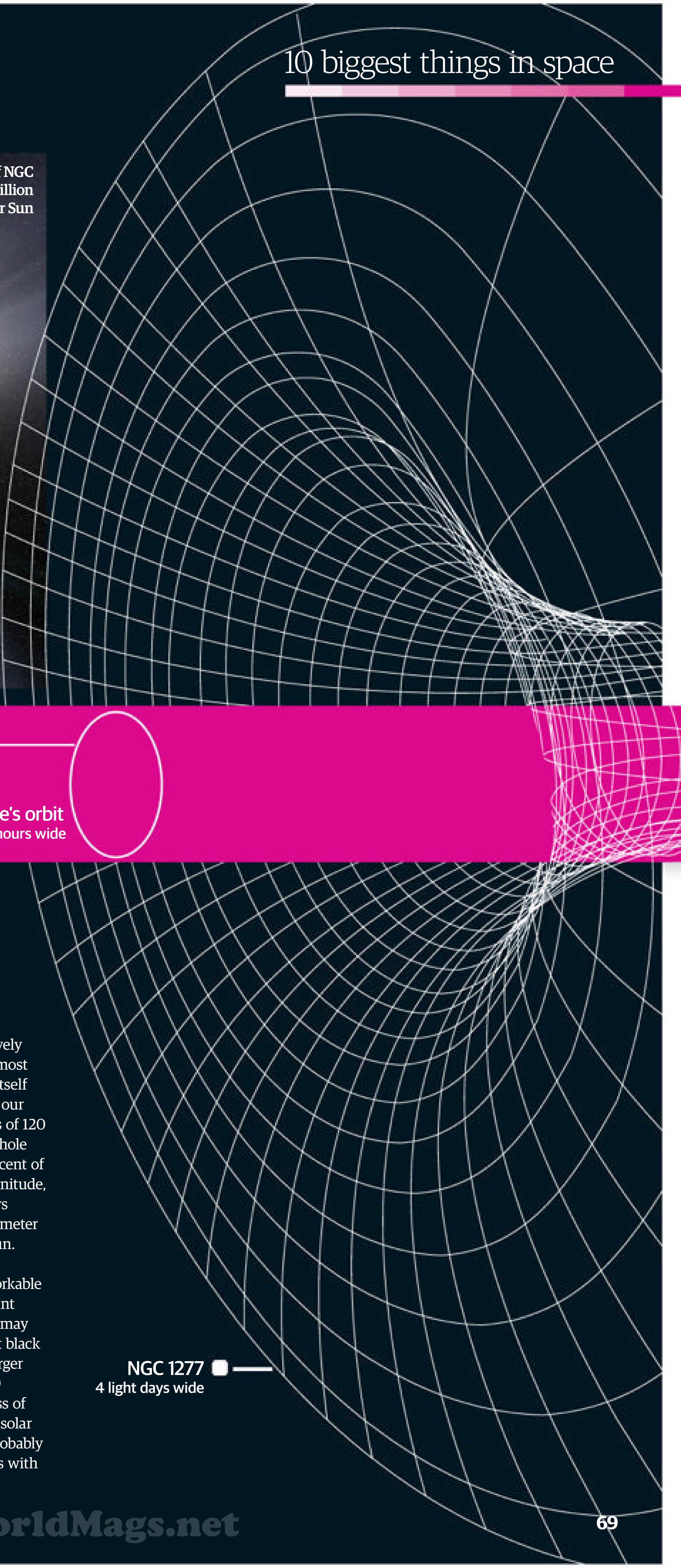


BIGGEST BLACK HOLE
NGC 1277

The biggest black hole whose mass has so far been properly measured lies at the heart of a galaxy called NGC 1277, 250 million light years from Earth in the constellation of Perseus – and it's a real whopper. While our own galaxy's central black hole has an estimated mass of 4.1 million Suns, the black hole in NGC 1277 is around 17 billion solar masses.

Astronomers discover and assess black holes in distant galaxies by measuring the orbits of the stars that surround them. Many have now been found, with masses equivalent to millions or even billions of Suns, but they usually follow a fairly strict relationship that limits the black hole to around 0.1 per cent of the host galaxy's mass – the more massive the galaxy, the bigger the black hole. In 2012, however, a team led by Remco van den Bosch of Germany's Max Planck Institute for Astronomy announced their discovery of 'supergiant' black holes in relatively small galaxies. NGC 1277 is the most impressive of these: the galaxy itself contains a lot less material than our Milky Way, with an overall mass of 120 billion Suns, so its central black hole accounts for a staggering 14 per cent of all its mass. At this order of magnitude, it's probably about four light days across – roughly 11 times the diameter of Neptune's orbit around the Sun.

As yet, astronomers are still struggling to come up with a workable theory to explain these supergiant black holes. However, NGC 1277 may not hold its record as the biggest black hole of all for long. The much larger giant elliptical galaxy NGC 4889 contains a black hole with a mass of between 6 billion and 37 billion solar masses, and astronomers will probably find a way to lock down its mass with more accuracy soon.

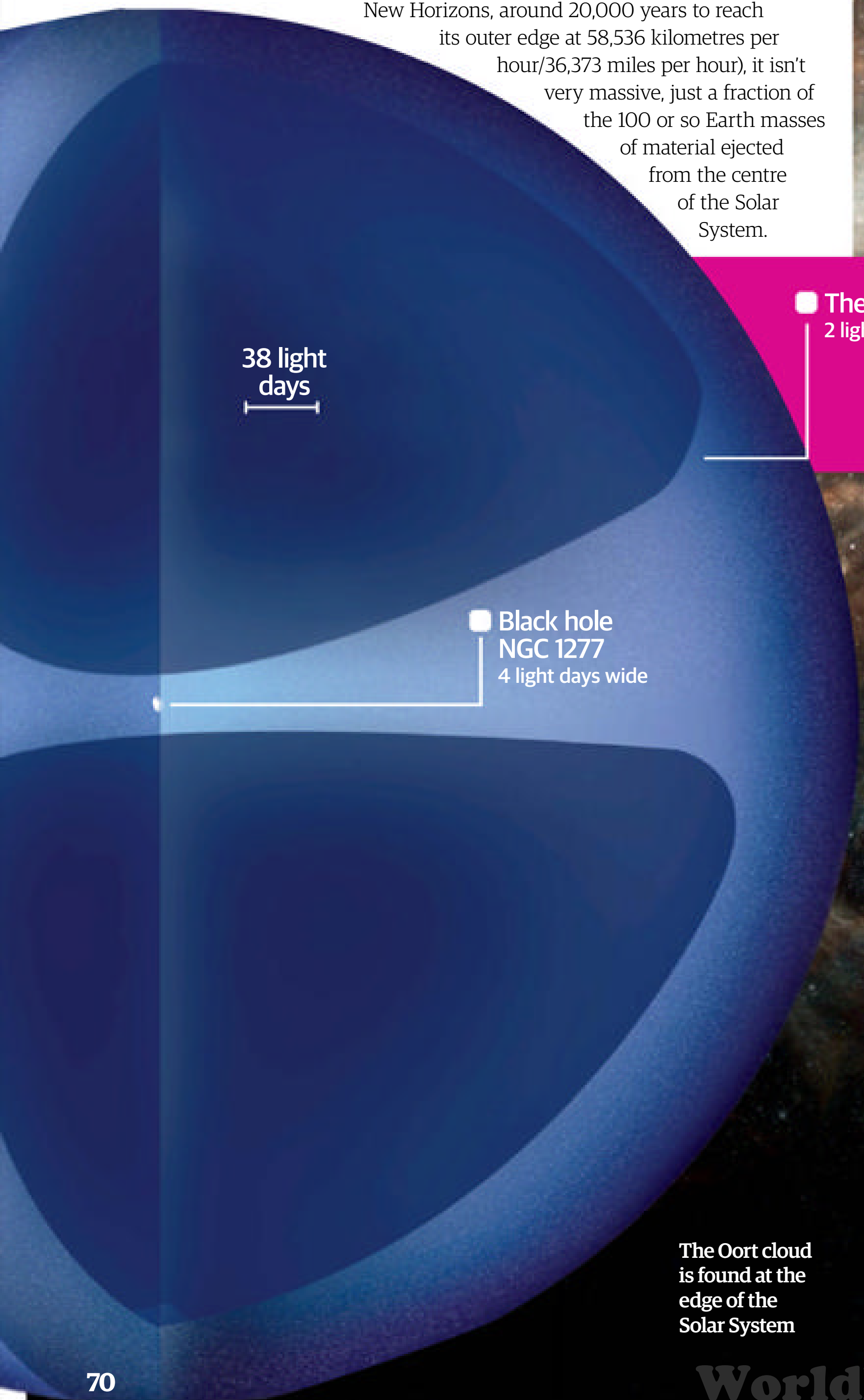


BIGGEST ICE SPHERE

Oort cloud

It's incredible to think that a black hole can be so big that it would take light four days to cross from end to end. But far, far out beyond Neptune's orbit is something much bigger: the Oort cloud. It's an enormous region of space encapsulating the planets that stretches 50,000 AU from the Sun to around 100,000 AU in diameter at its outer boundaries: from one side to another it's about two light years long.

It's made of water, ammonia and methane ice in the form of icy particles and trillions of larger bodies. It's suspected that many of the Solar System's comets were born here and some trans-Neptunian objects (objects that orbit the Sun at a greater average distance than Neptune) are Oort cloud members too. It's divided into two distinct regions, the inner and outer Oort cloud, containing several trillion comets larger than one kilometre (0.62 miles) in diameter. Considering the size of the Oort cloud (it would take our current fastest spacecraft launch, New Horizons, around 20,000 years to reach its outer edge at 58,536 kilometres per hour/36,373 miles per hour), it isn't very massive, just a fraction of the 100 or so Earth masses of material ejected from the centre of the Solar System.



The Oort cloud is found at the edge of the Solar System

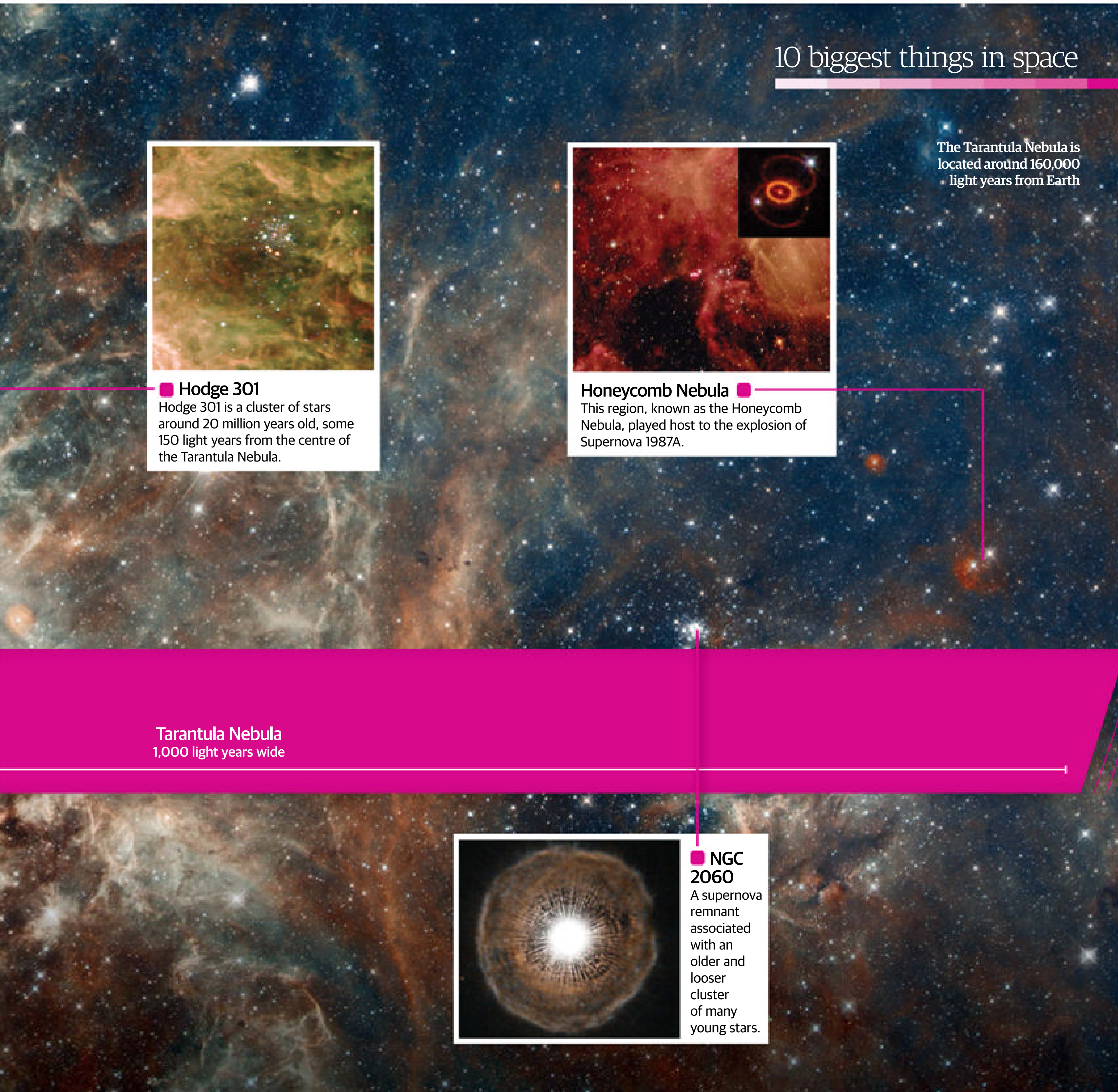
R136
This cluster at the centre of the nebula, is home to the most massive stars in the known universe.

BIGGEST NEBULA

Tarantula

The largest known nebula in the universe is many times larger than the Oort cloud and far more massive, with a star cluster at its core which is 450,000 solar masses alone. The Tarantula Nebula is right on our cosmic doorstep in the Large Magellanic Cloud (LMC), which is one of several satellite galaxies orbiting around the Milky Way itself. With a diameter of roughly 1,000 light years, the Tarantula Nebula (which also goes by the names 30 Doradus and NGC 2070) is a seething cauldron of starbirth containing millions of Suns' worth of star-forming material, approximately 160,000 light years from Earth. It's so brilliant that, if placed in our own galaxy at the distance of the famous Orion Nebula, it would cover half the sky and be bright enough to cast shadows.

The Tarantula Nebula gets its name from the spider-like shape formed by its brightest regions, and was mistaken for a star by the first astronomers that viewed it. It lies on the front edge of the irregularly shaped LMC, and owes its huge size to compression of the galaxy's gas and dust as it moves



The Tarantula Nebula is located around 160,000 light years from Earth

Hodge 301
Hodge 301 is a cluster of stars around 20 million years old, some 150 light years from the centre of the Tarantula Nebula.

Honeycomb Nebula
This region, known as the Honeycomb Nebula, played host to the explosion of Supernova 1987A.

Tarantula Nebula
1,000 light years wide

NGC 2060
A supernova remnant associated with an older and looser cluster of many young stars.

through the intergalactic medium surrounding our own galaxy. The result is an enormous 'starburst' region in which star formation is proceeding at a much faster rate than it does in most galaxies.

Like all star-forming nebulas, the Tarantula Nebula owes its brilliance to fluorescence. High-energy ultraviolet radiation from the hot young stars within it energise atoms of hydrogen and other gases, and they return to their normal state by emitting visible light. Darker regions within the Tarantula Nebula are created where light-absorbing dust is silhouetted against the brighter background.

Most of the energy that illuminates the nebula comes from two major star clusters that lie close to its heart, known as Hodge 301 and R136. Hodge 301 is the older of the pair, and has drifted some 150 light years from the centre in the 20 million years or so since it formed. It contains dozens of massive stars whose hot, fast-moving stellar winds are carving out a hollow as it moves through the surrounding gas. R136, meanwhile, lies in the very densest starbirth region and is just 1 to 2 million years old. It is dominated by rare blue-white stars of a type that are so massive and short-lived they normally destroy themselves as supernovas within a few million years of formation. At the centre of the cluster, these stars form a tight knot that was once thought to be a single enormous star. In the last few years astronomers have discovered that it is actually a tightly packed cluster-in-a-cluster, but its brightest single component is our favourite massive Wolf-Rayet star, R136a1. In fact, R136 contains so much mass that astronomers expect it to break the normal rules of cluster evolution. Instead of drifting apart, its gravity will probably hold it together, eventually producing a closely bound ball dominated by thousands of fainter, more long-lived stars, known as a globular cluster.

With so many massive stars, it's little wonder that supernovas are relatively common in the Tarantula. The last naked-eye supernova, seen in 1987, occurred on its outskirts, and its gas is sculpted by the still-expanding shockwaves from earlier explosions.

BIGGEST GALAXY IC 1101

The largest galaxies in the universe are giant ellipticals – huge clouds containing trillions of stars whose overlapping individual orbits create an enormous, fuzzy-edged ball. These monsters can grow to be ten times the size of the Milky Way, but even by these standards, IC 1101 stands out: it has a diameter more than 50 times that of the Milky Way, and is roughly 2,000 times heavier.

IC 1101 lies at the heart of a galaxy cluster called Abell 2029, over a billion light years from Earth. The cluster has an overall mass of around 100 trillion Suns, though most of this is invisible 'dark matter'. Only the galaxy's central region is bright enough to be seen in visible light (it was discovered in 1790 by William Herschel). Despite its relative brightness and early discovery, however, IC 1101's true scale was only realised in 1990 when astronomers detected the faint stars orbiting in its outskirts for the first time. More recent images from the Hubble Space Telescope have confirmed that it is roughly 5 million light years across, while the Chandra X-ray Observatory has revealed an extended halo of hot gas spread across a similar region.

Giants such as IC 1101 are only found at the centre of old, densely packed galaxy clusters, and astronomers think they form from the collisions and mergers of smaller galaxies. Over time, these collisions heat up the star-forming gas within the galaxies, giving it enough energy to escape their gravity. This robs giant ellipticals of the ability to form new stars, so as their more massive, shorter-lived stars age and die, they end up containing only lower-mass, sedate red and yellow stars. The orbits of individual stars also become more chaotic until the kinds of structure seen in spiral galaxies disappear and only a ball of stars in overlapping orbits remains. At the centre of the galaxy, a supermassive black hole provides a gravitational anchor around which each star orbits. Meanwhile, the overall mass of this giant star cloud is still enough for its gravity to keep a loose hold on the surrounding hot gas, creating a halo of X-ray-emitting material around the giant elliptical galaxy, at the centre of the cluster.

IC 1101 is a giant elliptical galaxy 50 times wider than our own

Peter Eisenhardt

WISE project scientist

Do clusters and superclusters act as a single entity?
Groups are gravitationally bound. Then you have larger clusters a magnitude of ten bigger than groups, the largest gravitationally bound structures. When we say gravitationally bound, I mean bound in the same way Earth and the planets are bound to the Sun, except, there's not really a central, dominant equivalent of the Sun.

Can superclusters get bigger than the LQG?
The distribution of galaxies is not the same if you look along the distance between here and the Coma cluster – 300 million light years. The universe is lumpy [unevenly distributed] on that scale, but we know there's not much lumpiness on a factor of ten larger than this scale, because we've been able to probe out for much larger distances than 300 million light years. We can see that on the scale of a billion light years, the universe is pretty much the same no matter where you look. An important point is that the larger structures have been at the centre of the realisation that most of the gravity is coming from dark matter. And they're important for understanding the history of the universe because the size of these structures tell us what has happened over the history of the universe.

Between the clusters are voids: are those truly empty?
I would hesitate to say there's nothing in them. Voids are substantially under-dense. Every[where] in the universe today there is ionised hydrogen – protons and electrons. The density of that ionised hydrogen doesn't vary tremendously, so in the voids, it's not vastly less dense than in the clusters.

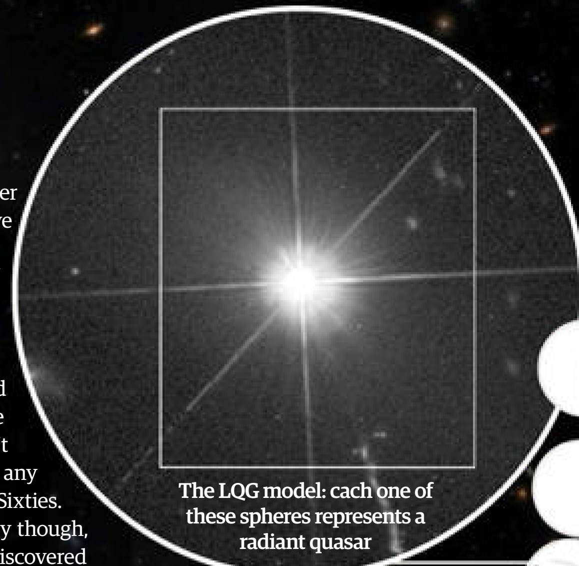
What's 'big' for a cosmologist?
300 million light years isn't an instant, but it's more or less contemporaneous. A billion light years is starting to be interesting. The nearest star being four light years away is still an awfully long way. It's mind-boggling how much we know having not gone the tiniest fraction of that distance.

BIGGEST VOID
Boötes void

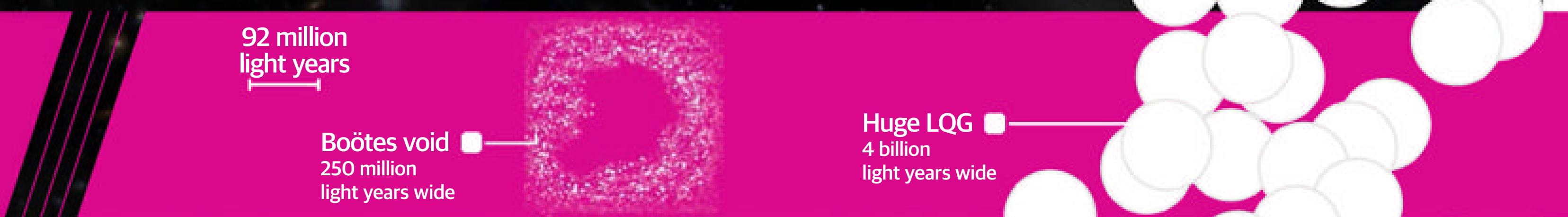
One of the biggest things we know of in the universe, weirdly, is nothing. Between galaxies there is intergalactic space, filled with gas, dust and ionised particles.

Scientists are studying this unfeasibly large, empty hole in space

Most of the time, there's relatively little distance between them: we're talking hundreds of thousands of light years that, in the grand scale of the cosmos isn't so much to make a big deal of. But there are a few big places in our universe that are practically a vacuum, huge expanses of space with near to nothing in them. These are the supervoids and the biggest of them is the Boötes void, a spherical area in space 700 million light years from Earth near the Boötes constellation. Its diameter in the sky is 250 million light years and its volume is a staggering 236,000 cubic megaparsecs. To give you an idea of how much that is, a single cubic megaparsec is the equivalent volume of three cubic metres with 67 zeros after it. Put another way, we've been observing other galaxies for hundreds of years (even if we didn't appreciate exactly what they were at the time), but if the Milky Way had been in the centre of the Boötes void, we wouldn't have even known about any other galaxies until the Sixties. It's not completely empty though, 60 galaxies have been discovered in Boötes, but a space this large should contain an estimated 10,000 galaxies. By comparison, our galactic neighbourhood has nearly half the number of galaxies of Boötes in a tiny fraction of the same volume.



The LQG model: each one of these spheres represents a radiant quasar



BIGGEST SUPER STRUCTURE
Huge LQG

Our final giant is one of many super-structures that make up the known, observable universe. These galactic superclusters are made up of smaller clusters and groups relatively near to each other that, gravitationally, move in harmony.

A single supercluster typically contains thousands of individual galaxies: our own Milky Way galaxy, for example, is part of the Local Group of over 50 galaxies that is part of the much larger Virgo Supercluster. This contains more than 100 galaxy groups and clusters for a total number of galaxies that number in the tens of thousands. The Virgo Supercluster spans a respectable 100 million light years in diameter and until recently, the biggest known superclusters were around seven times wider.

But earlier this year, a team of scientists discovered the biggest object in the universe using data from the Sloan Digital Sky Survey. It stretches 4 billion light years across space and is so huge that it messes with conventional scientific theory on how the universe has evolved. The Large Quasar Group (LQG) consists of 73 quasars, incredibly radiant cores that surround supermassive black holes at the centre of enormous galaxies. The LQG, as it's known, is 9 billion light years away and is several times bigger than the previously understood upper limit for the largest cosmic structure (1.2 billion light years). It's thought that these ancient objects might represent an early stage of galactic evolution in the modern universe and the LQG itself, a rudimentary part of supercluster development.

In the last few centuries and the last few decades in particular, we've come a long way in our understanding of the scale and concept of the universe around us. To think that ancient Greek philosopher Anaxagoras was once convicted of 'impiety' for saying that the Sun was a 'mass of red-hot metal larger than the Peloponnesus' (a Greek peninsula of around 20,000 square kilometres/8,000 square miles)! With the advancement of observational technology and the launch of new telescopes like the James Webb Space Telescope, it's only a matter of time before another super-sized record is smashed and we have to revise our understanding of this giant universe.

So big, the LQG defies scientific theory

THE MOST POWERFUL FORCES IN THE UNIVERSE

Run for cover and shield your eyes! We explore the objects in the cosmos that pack the biggest punches of all

The universe is an incredibly violent place, populated by explosions and torrents of radiation, pulled this way and that by powerful fundamental forces, and lit up by active centres of galaxies and massive stars. All these forces are in interplay – supernovas create black holes, while gravity battles dark energy to decide the fate of the universe. Energies far greater than the Sun can produce in 10 billion years are wielded in a matter of seconds, and our knowledge of physics is put to the test by the most extreme and most powerful events in the universe.

THE EXPLOSION THAT CREATED THE UNIVERSE

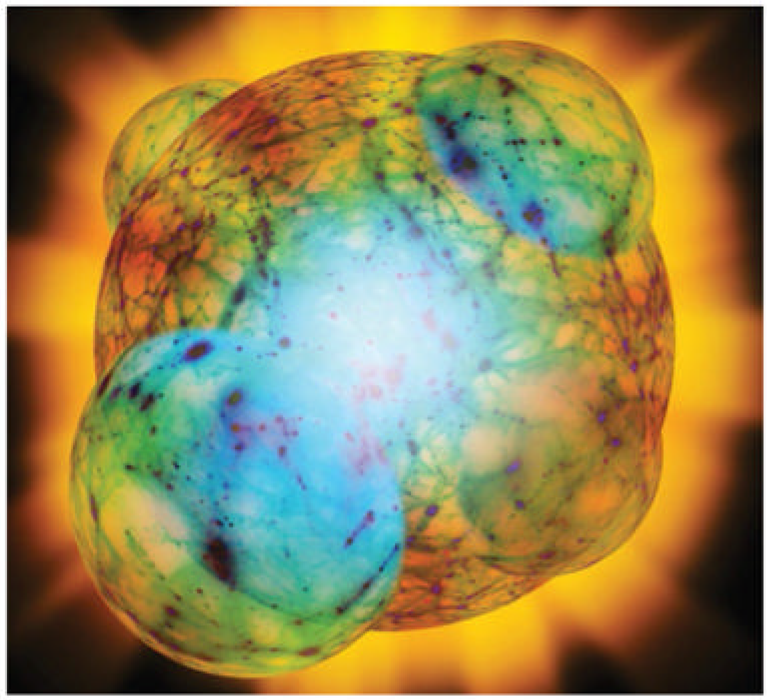
The Big Bang

Our universe sprang into existence around 13.77 billion years ago; a great event that created everything we know of - from stars and galaxies to planets and Solar Systems. Nothing existed before the Big Bang. While it's easy to imagine that a great explosion created our universe, this is far from the truth. Currently we understand that, at first, there was nothing and, during and after that moment, time and space came into existence - beginning as an infinitesimally small, infinitely hot and dense object. Just where it came from, is however, something experts are still not sure of.

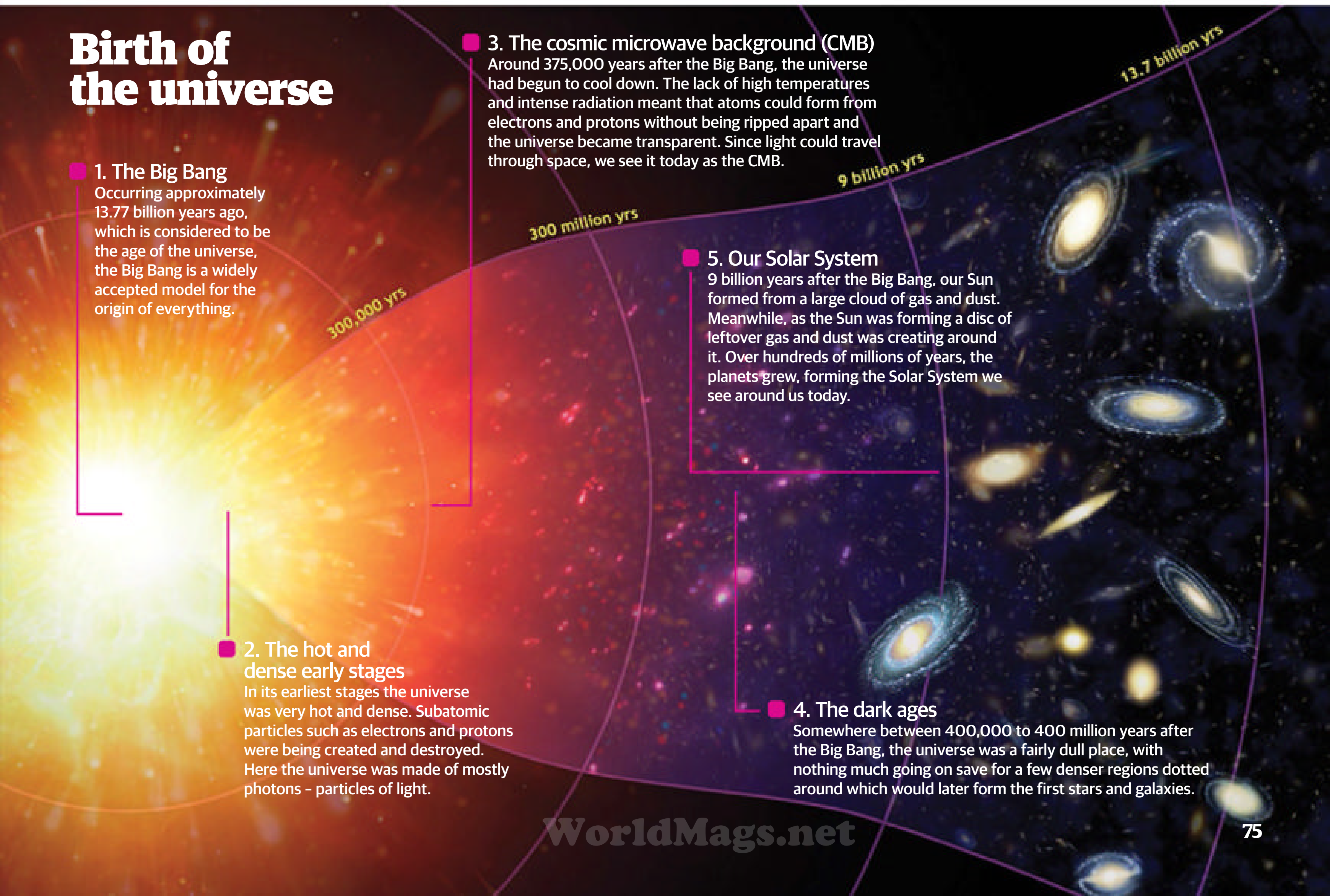
What we do know is that this point began to expand and is continuing to do so according to the rate at which galaxies are moving away from us. The story of how the cosmos came to be as it is today is a tale of high energies, thick 'fog' and sizzling temperatures which gradually calmed, cleared and cooled, creating the first particles and the beginnings of the fundamental forces that surround us. These are the electromagnetic, weak, gravitational and strong forces, the latter being the one that holds nuclei together.

As the universe cooled further it shifted from being radiation dominated to being matter dominated, introducing the hydrogen atoms along with the cosmic microwave background radiation - the thermal radiation that fills every part of the universe - which crackles its presence when radio dishes are turned upon it.

The final transformation saw the emergence of large-scale structures as the earliest stars, quasars, galaxies, clusters of galaxies and superclusters were added to the cosmic mix. ●



An artist's impression of the inflation theory which suggests that during the Big Bang, a false vacuum created a force which drove a very rapid expansion of the universe



POWERING THE EXPANSION OF THE UNIVERSE

Dark energy

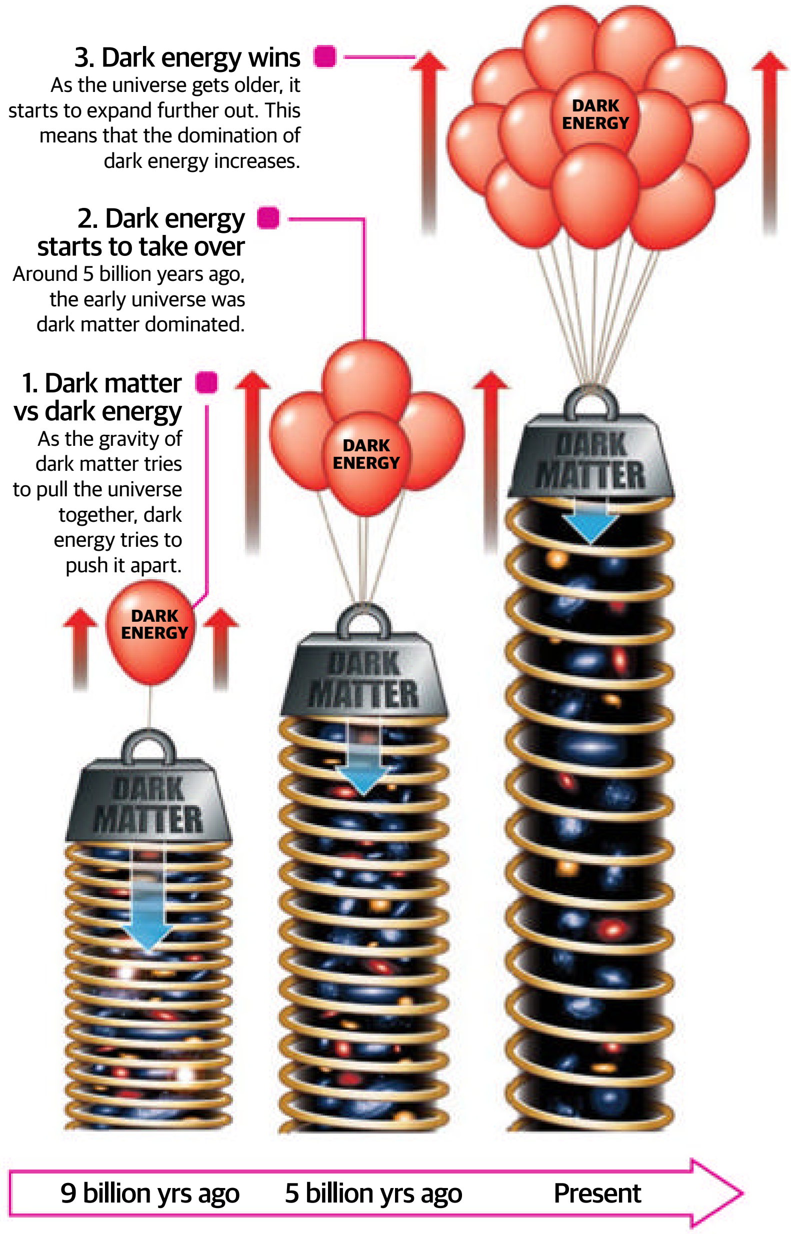
We can't see it, but we know it's there. The mysterious dark energy, which accounts for roughly 70 per cent of the universe, is the driving force behind why galaxies are moving away from us in an almost eternal expansion, which, according to experts, isn't showing any signs of slowing down.

Permeating through every corner of space, scientists didn't even realise it existed until 1997. Two groups of astronomers had been competing against each other to measure the expansion rate of the universe by using the light of supernovas. As the universe expands, the light is stretched and reddened. Because certain types of supernovas – the explosions of merging white dwarf stars – detonate with practically identical energy and luminosity, they believed it would be possible to measure their 'redshift' and consequently the expansion of the universe. They expected it to be slowing down – instead it was found that it was actually speeding up!

Nobody knows what dark energy is or even precisely how strong it is. It acts a bit like anti-gravity, pushing the universe apart. On the biggest scales it overcomes all of the other forces in the universe, including gravity, and that could prove to be bad news for the universe. If dark energy was to become too powerful, it could tear the universe apart in a 'big rip', starting with galaxy clusters, then galaxies themselves, then stars, planets, us and even our constituent atoms until the fabric of space and time itself is destroyed completely.

At best dark energy will accelerate the expansion of the universe so that every other galaxy is moved so far away from us that we will no longer be able to see them, but astronomers need not panic yet – this is not expected to happen for approximately another 2 trillion years.

A ring of dark matter can be seen in this image of galaxy cluster CI 0024+17



Gravity THE FORCE THAT BINDS THE UNIVERSE TOGETHER

In *Star Wars*, there was The Force – the mystical field that binds together all life. In the universe, however, there is another 'force' that binds together all matter, and that's the somewhat mysterious force of gravity. That famous (and probably false) story of an apple falling on Isaac Newton's head was only the beginning of gravity's remarkable story.

What makes the planets round? Gravity. What keeps us from floating away? Gravity. What causes temperatures and pressures to grow so high in the core of the Sun that it can ignite nuclear fusion? Gravity. What keeps the planets orbiting the Sun? Gravity. And so on.

So, gravity is a big deal. Newton's laws of motion and his law of universal gravitation describe how gravity operates in everyday life. However, things can get a little strange when we start to talk about really massive objects, or things that are moving at close to the speed of light. This is where Einstein's general theory of relativity comes in, describing such concepts as gravitational time dilation, black holes and neutron stars with immense gravity, gravity wells in space-time, and gravitational lenses where massive objects like galaxy clusters are able to bend and magnify the light of more distant objects. And when neutron stars merge, or black holes crash into each other, they unleash a torrent of 'gravitational waves' that ripple through space-time.

Nobody has ever detected a gravitational wave, but scientists are always on the lookout and hope to meet with some success in this area in the coming years.

Oddly, for a force that is so important, gravity is relatively weak on small scales. A bar magnet, for example, can overpower gravity, picking bits of metal up for fun. But on much larger scales gravity does dominate, holding entire galaxy clusters together. It's only when it comes face to face with the ever-growing force of dark energy that gravity starts to become unstuck.

Ultimately, the fate of the universe will be decided by this ongoing battle between gravity and dark energy: will dark energy rip the cosmos apart, or will gravity be strong enough in the long run to pull the universe back in a 'big crunch'? Only time will tell, but the end of the universe may be decided by one of these theories.

SO BRIGHT THEY CAN BE SEEN FROM THE EDGE OF SPACE

Quasars

They might be distant, but packing a punch of high energy and indescribable luminosity are quasars - objects believed to be glowing strongly since their creation in the universe's early days.

Usually found in the very centres of active galaxies, quasars are among the most powerful objects in the universe; with most throwing out a luminosity equivalent to around 2 trillion Suns, while others emit strongly as sources of radio emission and gamma rays. So what gives them so much power?

In the nuclei of the galaxies they occupy, a supermassive black hole munches on the material from the disc of gas around it. This gas is then fed into the centre of the galaxy with the dazzling quasar light all coming from this million-degree hot disc and the jets of energy it unleashes. The jets form because the disc is a tangle of magnetic fields that become tightly wound as the disc rotates, trapping charged particles within them until they're fired out at almost the speed of light. It's only when we look almost head-on at these jets that we see a quasar. Indeed, they are so bright and powerful they can be seen right across the known universe.

Powerful radiation

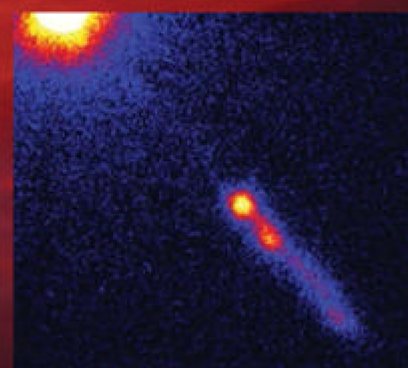
The most luminous quasars radiate the equivalent of the output of around 2 trillion Suns. Radiation is emitted in the X-rays to the far-infrared, along with a peak in the ultraviolet-optical bands. Some quasars also shine strongly with radio emission and gamma rays.

Distant but bright

Capable of emitting up to a thousand times the energy output of our entire galaxy, quasars, while incredibly distant, are the most luminous, powerful and energetic objects currently known.

Accretion disc power

Quasars are believed to be powered by the accretion of material into centralised supermassive black holes, some of these high-gravity objects have masses of over 1 million solar masses.



An X-ray image of quasar 3C 273 and its jet. This quasar is the closest to Earth at a distance of almost 3 billion light years

Gravity wells

The Sun

Since our Sun is so heavy, its gravity well is by far the deepest.

Inner planet gravity

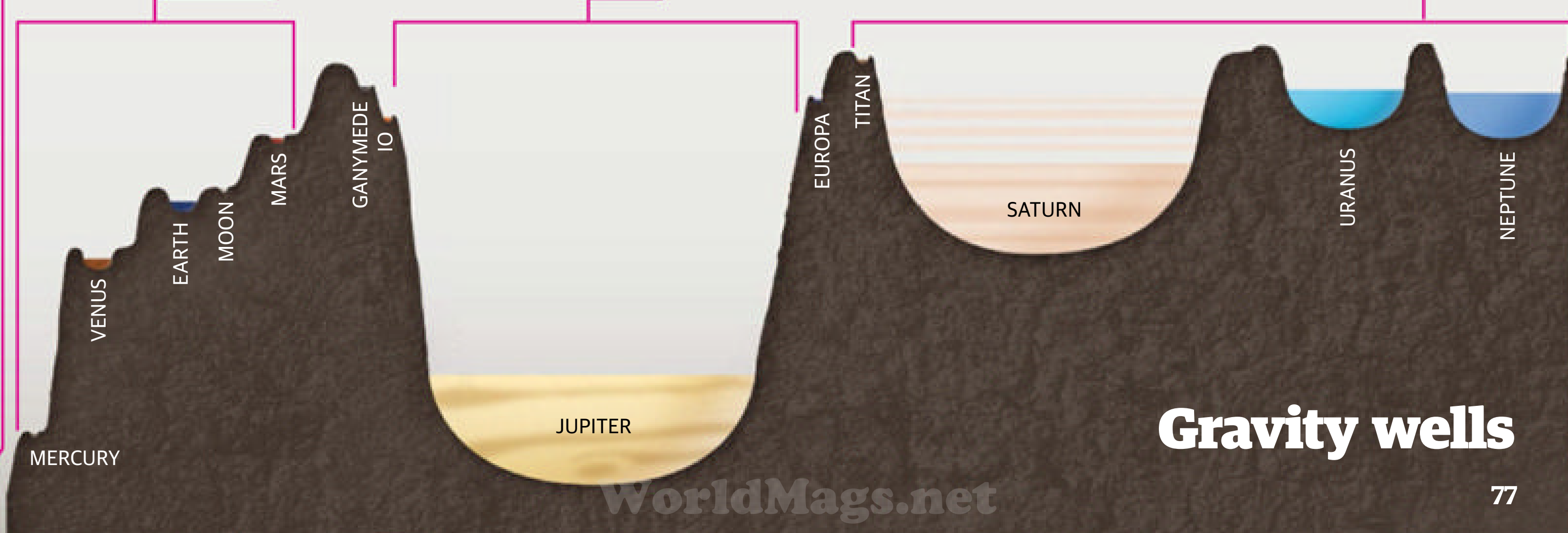
Out of the terrestrial planets, Earth has the deepest gravity well. The deeper the well, the harder it is to escape the gravity of the planet.

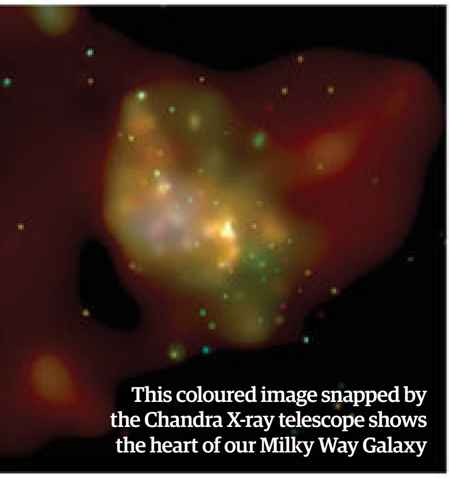
Jupiter's gravity well

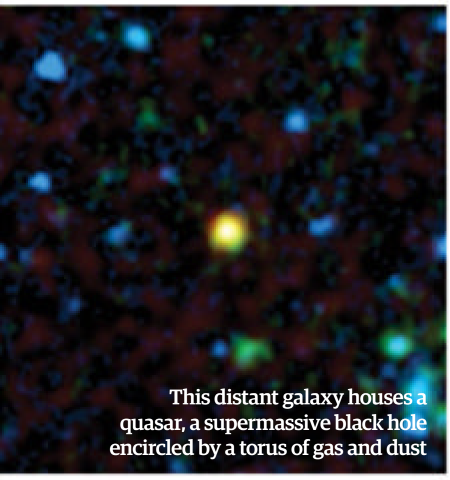
Because this gas giant is much more massive than each of the planets in our Solar System, it has the deepest gravitational well. In comparison, its moons have shallower dips which are quite easy to escape.

Outer planet gravity

Out of Saturn, Uranus and Neptune the deepest gravity well is made by Saturn.




This coloured image snapped by the Chandra X-ray telescope shows the heart of our Milky Way Galaxy


This distant galaxy houses a quasar, a supermassive black hole encircled by a torus of gas and dust

THE POWER TO HARNESS A GALAXY

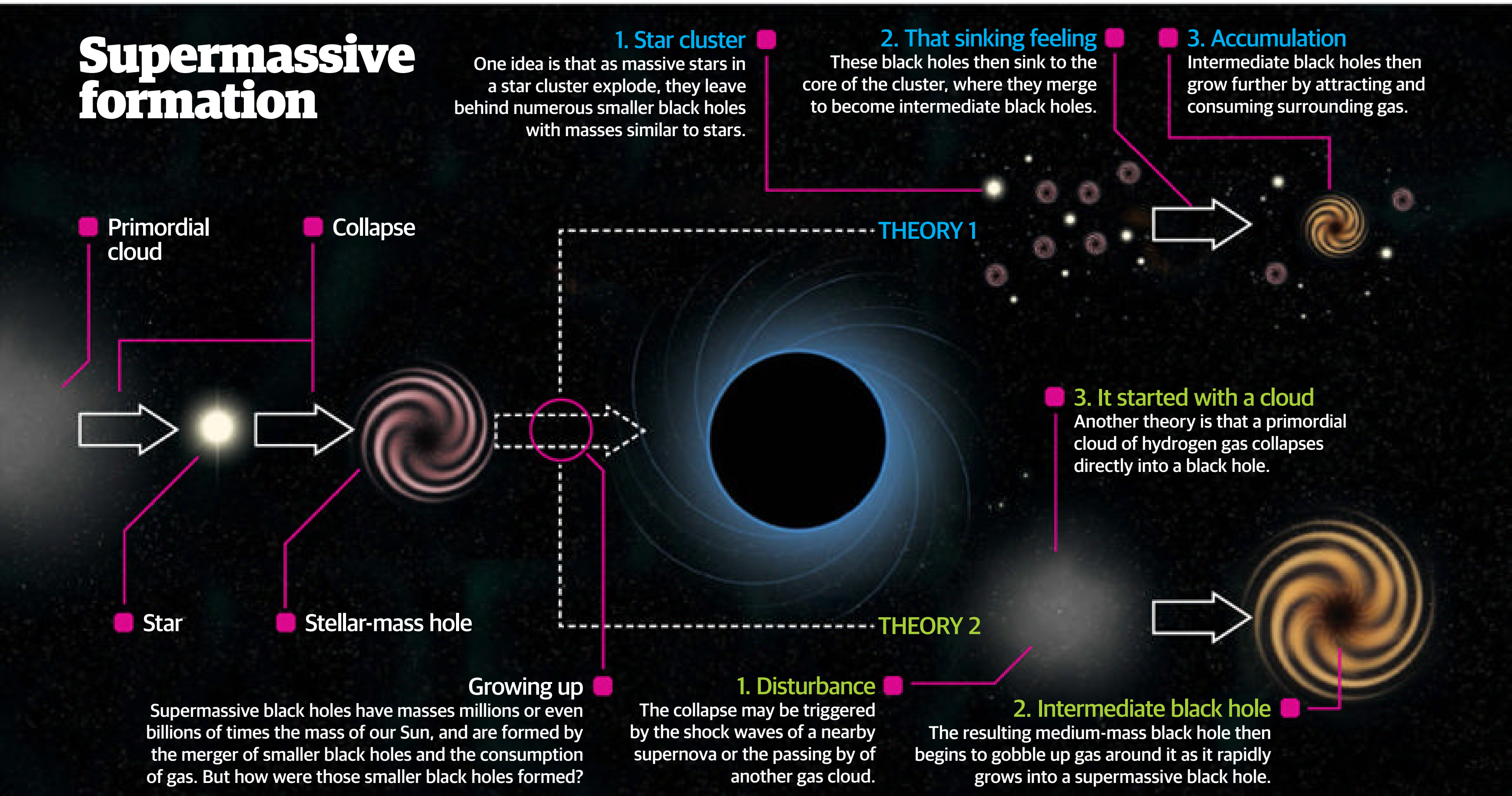
Supermassive black holes

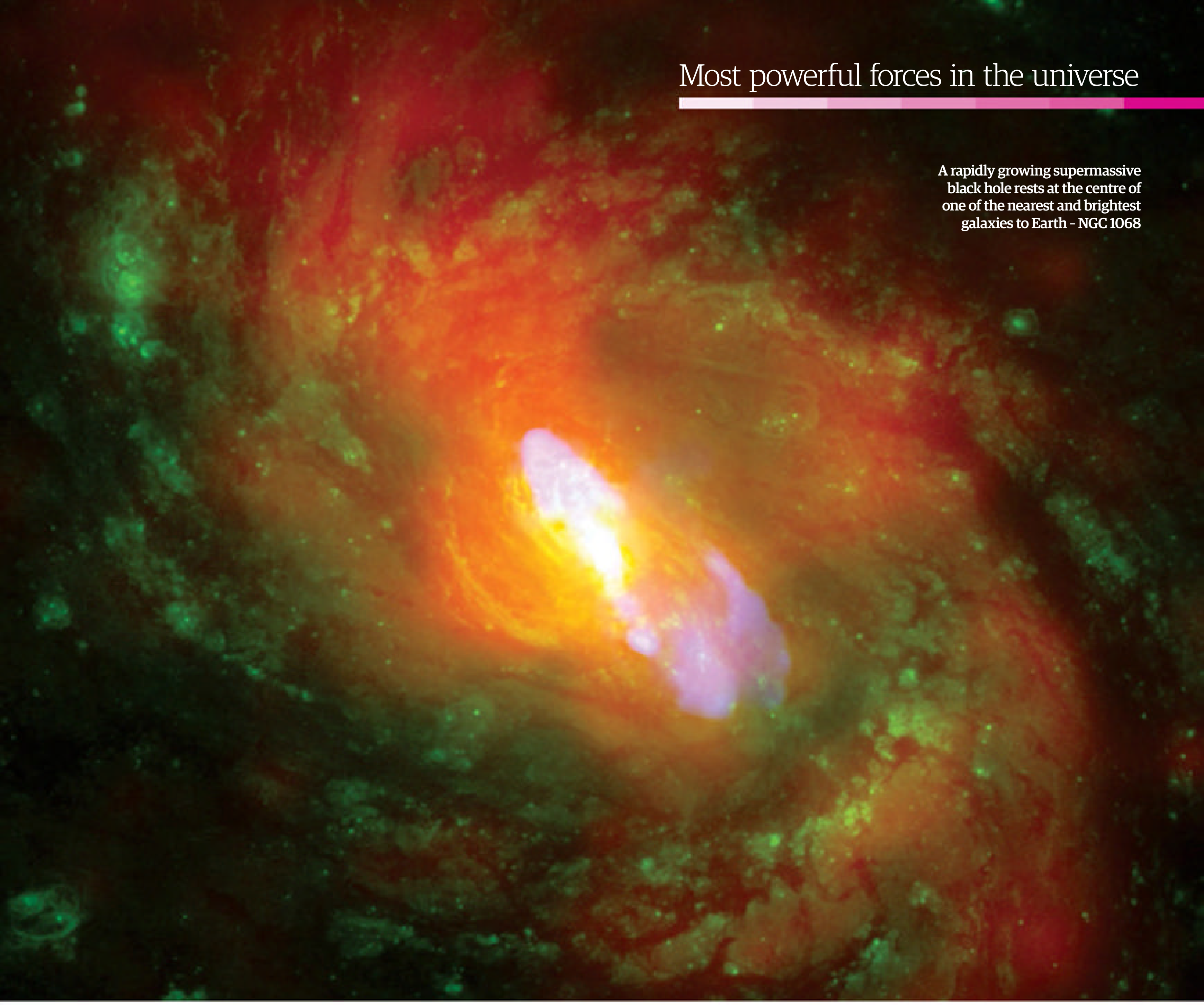
The ultimate consequence of gravity is a black hole. Imagine a region of space where gravity has caused a star to collapse at the end of its life to a point so small and dense that its gravity is practically infinite and completely overwhelms everything else. It's so strong that not even light can escape its grasp - the point of no return is known as the event horizon - explaining where the name black hole came from. And black holes don't come any more massive than a hefty supermassive black hole. With a mass ranging anywhere from hundreds of thousands to billions of times the mass of the Sun, these exotic high-gravity objects are, more often than not, the centrepiece of the many galaxies that litter our universe. Our own Milky Way even has one, called Sagittarius A*, which is a monster of around 4.3 million times the mass of our Sun, located deep in the middle of our galaxy amid myriad stars and vast clouds of gas and dust. So powerful are these galaxies that they have the strength to switch star formation in a galaxy on and off at will.

Think back to quasars - these are the most extreme form of active supermassive black hole. But less energetic black holes can still produce lower power jets, yet even though they're lower power, they still dominate the galaxy that they are in. Stars need gas to form, and the gas in galaxies often falls on to them from wandering clouds of intergalactic gas. Yet as clouds fall on to galaxies, and as the galaxies merge with other galaxies, gas gets funnelled towards the black hole, ending up in a disc surrounding it, some of which is then beamed back out into the galaxy by jets, or 'winds', of stellar radiation.

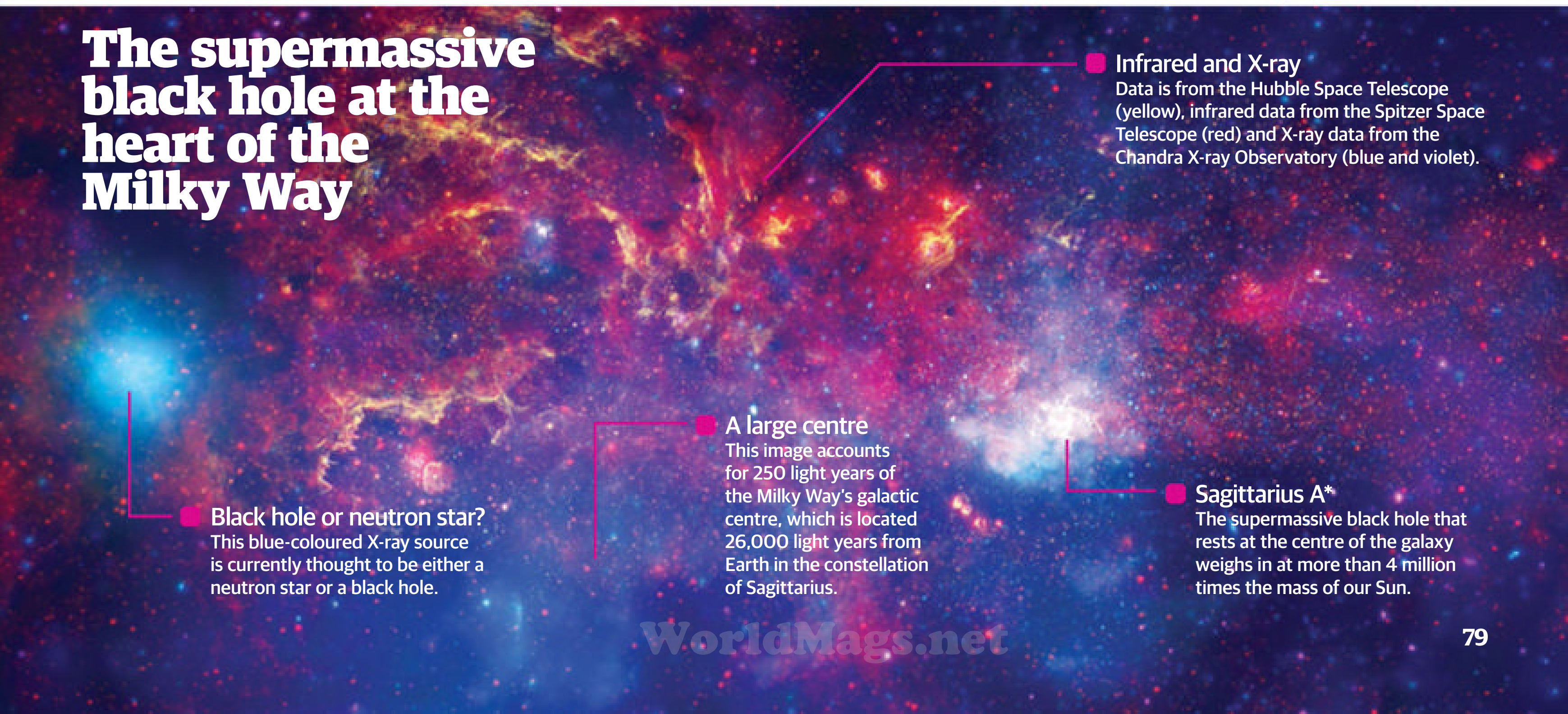
These jets and radiation heat the gas that is creating stars, causing it to become too hot for star formation and sometimes even blowing right out of the galaxy itself. This is called feedback, and when it happens it brings star formation in a galaxy to a stuttering halt.

> "Sagittarius A* is a monster of around 4.3 million times the mass of our Sun"





A rapidly growing supermassive black hole rests at the centre of one of the nearest and brightest galaxies to Earth - NGC 1068



The supermassive black hole at the heart of the Milky Way

Infrared and X-ray
Data is from the Hubble Space Telescope (yellow), infrared data from the Spitzer Space Telescope (red) and X-ray data from the Chandra X-ray Observatory (blue and violet).

Black hole or neutron star?
This blue-coloured X-ray source is currently thought to be either a neutron star or a black hole.

A large centre
This image accounts for 250 light years of the Milky Way's galactic centre, which is located 26,000 light years from Earth in the constellation of Sagittarius.

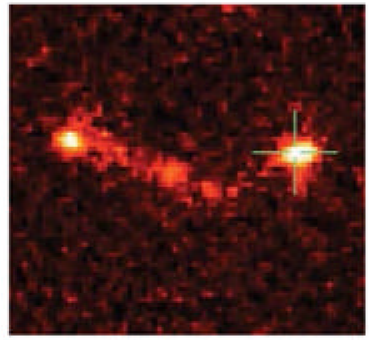
Sagittarius A*
The supermassive black hole that rests at the centre of the galaxy weighs in at more than 4 million times the mass of our Sun.

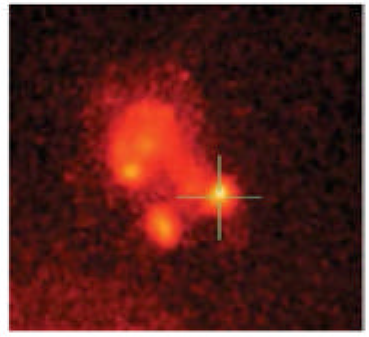
THE ENERGY OF A THOUSAND SUNS

Gamma ray bursts

Gamma-ray bursts (GRBs) signal the biggest explosions in the universe. They were discovered in 1973, after analysis of data from the Vela satellites, which the USA launched to try to detect Soviet nuclear tests in space. Instead, they found ferocious bursts of gamma rays from outer space. It took almost 25 years to figure out what they were. Scientists call them 'collapsars'. When the most massive stars of all reach the end of their lives, they can no longer hold back gravity and their core collapses into a black hole. Gas from some of the layers surrounding the core rain down on to it and, just like how the black holes in quasars produce jets, so do the black holes inside the collapsing star. All of this happens in merely a fraction of a second, and the jets blast out through the star's outer layers at close to the speed of light, as the star explodes.

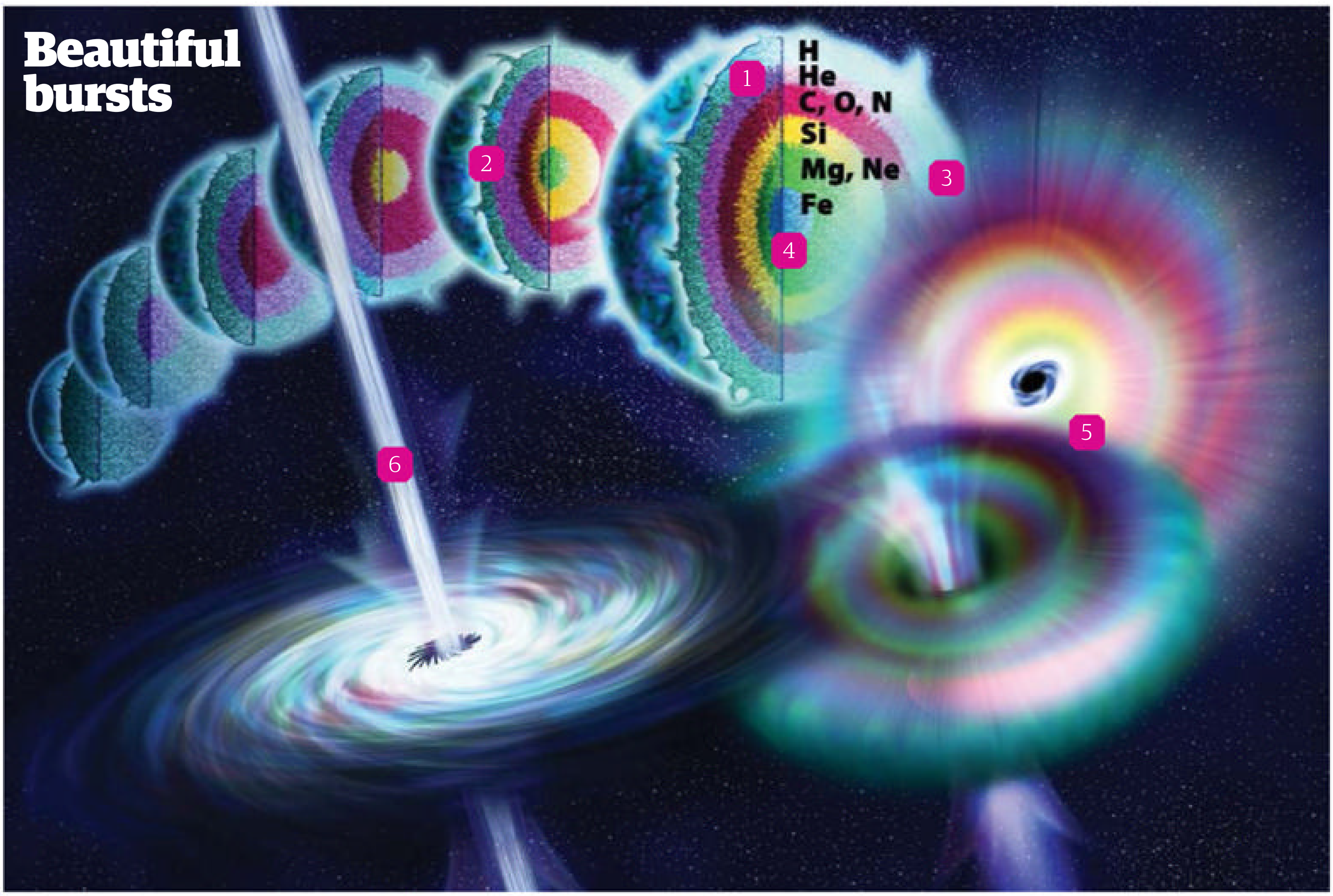
But this isn't what creates the gamma rays. The jets are formed from highly entwined magnetic fields, and when charged particles like electrons and protons spiral around magnetic fields like this, they produce gamma rays, and it's these gamma rays that we see as a burst. As for their power, there's nothing else like them in the known universe, releasing the equivalent amount of energy that a thousand Sun-like stars will release over their entire lifetimes! If a GRB's energy could be harnessed on Earth, it would meet the world's energy demands for billions of years.





A selection of images of galaxies that host long-duration gamma-ray bursts as taken by the Hubble Space Telescope

Beautiful bursts



1. Fusion
Stars generate energy through nuclear fusion. In massive stars it is via the CNO – carbon, nitrogen, oxygen – cycle, which acts as catalysts for fusion involving hydrogen atoms.

2. Onion layers
Nuclear fusion of hydrogen creates helium. Temperatures grow so high that the helium begins to fuse to create oxygen, then nitrogen, carbon, silicon and so on.

3. Living fast
Massive stars struggle to stay aloft against the pull of gravity, so they have to generate a lot of energy, which uses up their vast stores of gas in just a few million years.

4. Iron star
Massive stars end up with cores of iron, which cannot undergo further nuclear fusion without putting in more energy than it produces. Fusion ceases in the star's core.

5. Collapse
As the massive star reaches the end of its life and is unable to generate any more energy, the core of the star begins to collapse in on itself to form a black hole.

6. Jets
Gas inside the star swirls around the black hole and forms powerful jets that destroy it in a hypernova. Charged particles spiralling around the magnetic jets produce gamma rays.

THE POWER OF AN EXPLODING HYPERGIANT

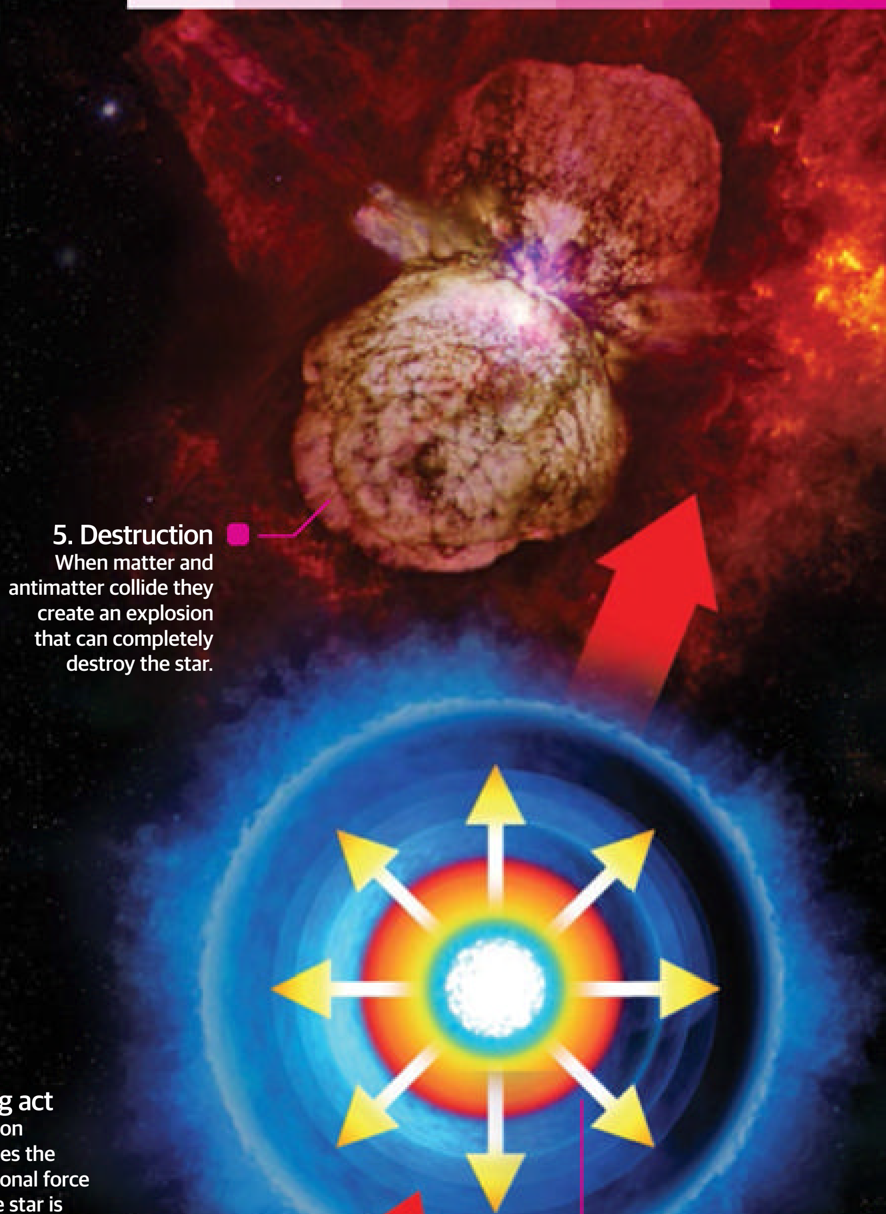
Hypernovas

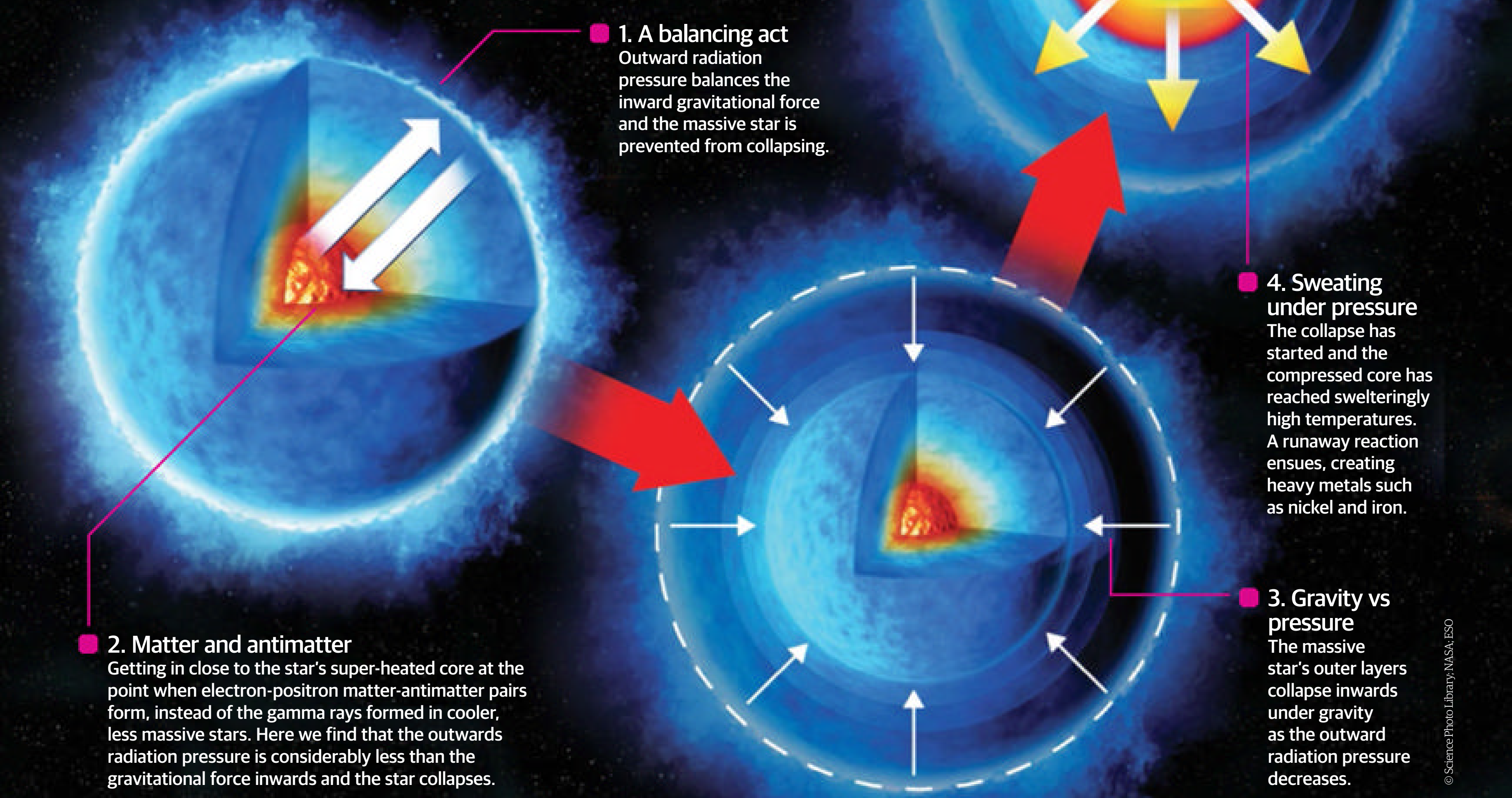
As you might imagine, the supernovas that create gamma-ray bursts are no ordinary type of exploding star; instead we call them hypernovas, and they make normal supernovas look like a mere pop in comparison.

Hypernovas can be 20 times more luminous and up to 50 times more energetic than a normal supernova. It's not entirely clear why hypernovas are different to normal supernovas, but mass undoubtedly has something to do with it: some stars like Eta Carinae have masses around 100 times that of our Sun, while other stars that explode as supernovas may have only a dozen solar masses. In addition, massive stars that have been deprived of heavy elements - elements heavier than hydrogen or helium - have a tendency to explode as hypernovas.

However, not all hypernovas create gamma-ray bursts. It seems the most extreme examples are completely annihilated without even leaving a black hole behind. These are known as 'pair instability' supernovas and happen when electrons and their anti-particles - or positrons - are formed en masse by collisions between energetic gamma rays and atoms inside the dying star.

Not only does this lead to reduced pressure inside the supermassive star, which then prevents the core of the star from fully collapsing to create a black hole, but when matter and antimatter come into contact with each other in this way they create what's known as a runaway thermonuclear explosion that utterly destroys the star, without leaving a black hole remnant behind.





HUBBLE'S GREATEST DISCOVERIES

Join us as we take a tour of our favourite images by this iconic space telescope

The Hubble Ultra-Deep Field

INTERVIEW BIO

Dr Mario Livio
Senior astrophysicist at the Hubble Space Telescope Science Institute
Dr Mario Livio is an astrophysicist specialising in exciting stuff like black holes, neutron stars, white dwarfs and supernova explosions. He has worked with Hubble at the Space Telescope Science Institute since 1991 and has published over 400 scientific papers and five popular science books.

This year, the Hubble Space Telescope is celebrating its 25th year in space. Over the past two and a half decades, it has made more than a million observations, provided the data for over 10,000 scientific publications and it has given us a breathtaking window out into the far reaches of the universe from its position beyond the haze of our atmosphere.

Hubble was the brainchild of American astrophysicist Lyman Spitzer Jr. and its construction took almost a decade, completed in 1985. However, its journey into space was complicated. Its launch was delayed by the Challenger disaster in 1986, which claimed the lives of seven astronauts and by the time it finally arrived in orbit in April 1990, its first images were blurry. To the dismay of the team, the carefully crafted 2.4-metre (94.5-inch) mirror had a spherical aberration, a microscopic fault that prevented the light being properly focussed.

Hubble was designed to be able to dock with the Space Shuttle, allowing repairs and upgrades to be performed in space. A series of corrective mirrors were installed by intrepid astronauts in a week-long mission in 1993, acting like a pair of glasses and bringing the light into focus. Since the repair the telescope has been upgraded on a further four occasions and has gone on to capture thousands of stunning, high-resolution and iconic images.

Hubble is responsible for some of the biggest scientific discoveries of the space age. It showed that dark energy is accelerating the expansion of the universe and allowed scientists to pinpoint its age to between 13 and 14 billion years. And it has shown that there are supermassive black holes at the centres of almost all galaxies.

In its 25 illustrious years in space, Hubble has taken some of the most breathtaking images of the cosmos and in the process this amazing feat of engineering has captured the hearts and minds of the adoring public like no other space telescope has done before. ■

The galactic rose

This stunning image was released as part of Hubble's 21st birthday celebrations in 2011. The cosmic rose at its centre is formed by two interacting galaxies known together as Arp 273. The image was captured using the Wide Field Camera 3 (WFC3) and filters were used to distinguish between ultraviolet, blue and red light. A small galaxy called UGC 1813 viewed side-on from the Earth, forms the stem of the rose while the flower itself is a galaxy known as UGC 1810, which is five-times bigger. Astronomers believe that a past collision pulled the larger galaxy into its distorted, petaled shape. The ring that encircles UGC 1810 indicates that the smaller galaxy burst straight through as they collided, passing off-centre through the plane of the spiral and pulling its arms into a ring. As a result of the collision the centre of the small galaxy has lit up and the larger galaxy is studded with massive hot blue stars born out of the chaos. At the top right of the larger galaxy, there is another visible mini spiral, along with a blue burst of young star activity.

The sombrero galaxy

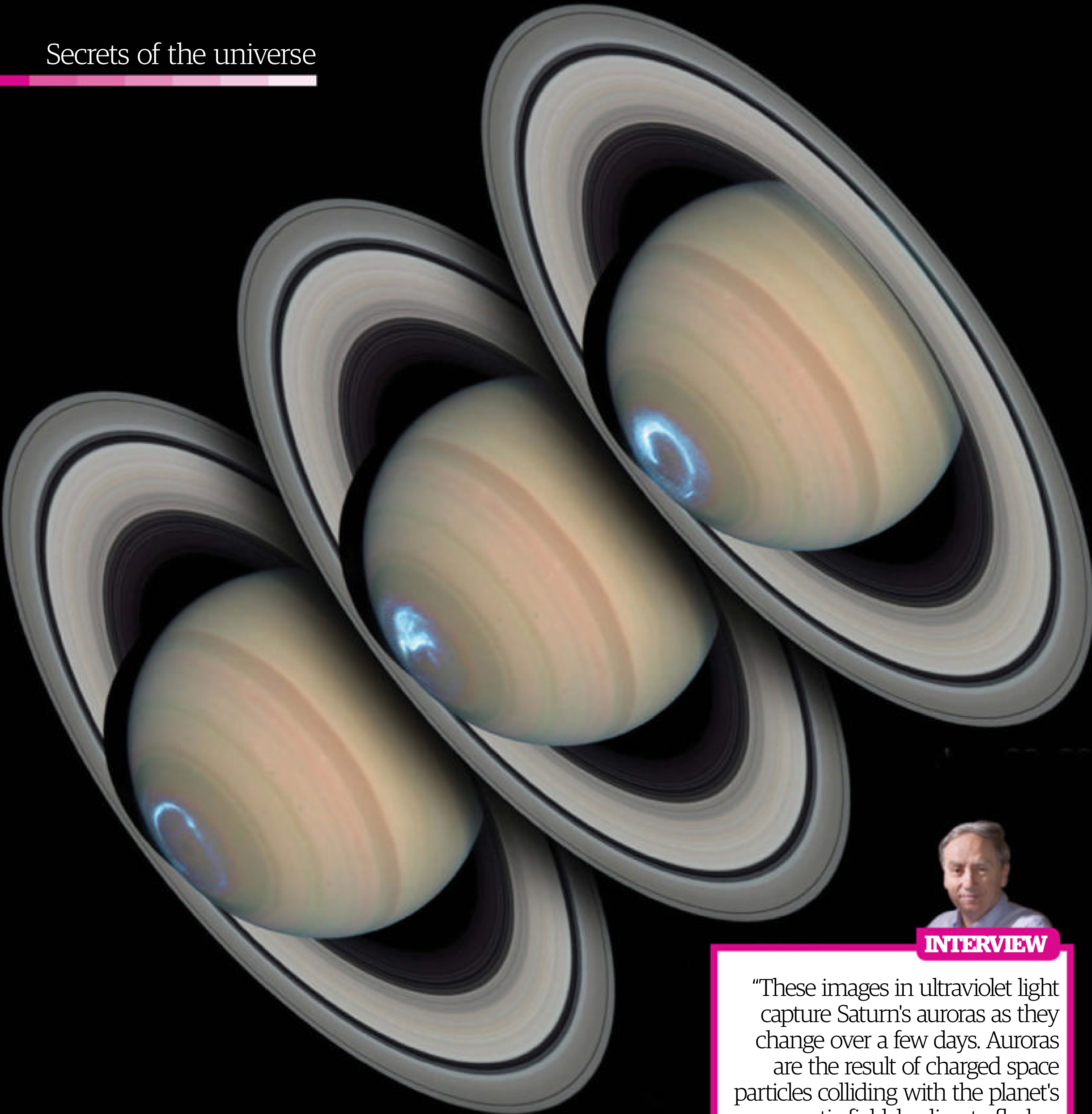
This incredibly detailed image of M104 was captured by the Hubble's Advanced Camera for Surveys. It is one of the biggest Hubble images ever taken, and it was stitched together from six separate exposures and used red, green and blue filters to create a true-colour representation.

The galaxy, nicknamed the sombrero galaxy after its wide, flat shape, is one of the most massive objects in the Virgo cluster. It was originally thought to be a star, but is moving away from us at speeds of over 1,127 kilometres (700 miles) per second and it is now known to measure 50,000 light years in diameter. It is almost the same age as the Milky Way, with globular clusters dating back 10 to 13 billion years.

In the very centre is a second disc, which appears at an angle to the main disc of the galaxy. It emits bright X-ray radiation and is thought to belong to a supermassive black hole measuring one billion solar masses.

INTERVIEW

"This visually stunning galaxy is about 28 million light-years from Earth. We view it almost edge-on. The main reason I like this image is that Hubble has captured the dust lanes in the galactic ring that surrounds the central bulge with such a resolution that the image looks almost three-dimensional. Around the galaxy you can see a collection of between 1,000 and 2,000 globular star clusters. This is about ten-times more than the number of clusters that surround the Milky Way."



The auroras of Saturn

In 2003, Hubble collaborated with the Cassini spacecraft to monitor the auroras in Saturn's atmosphere. Hubble's Advanced Camera for Surveys captured the visible light images of the outline of the planet and its Space Telescope Imaging Spectrograph revealed the ultraviolet glow of the auroras as they moved through the atmosphere. What they saw was auroras that last for days on end and glow bright throughout.

With Cassini's help, we know that these auroras are created by pressure changes in Saturn's atmosphere. As the solar wind increases, the auroras brighten and shrink in diameter.

Although the aurora seems to glow a bright, icy blue in this image, on the surface of Saturn the spectacle would appear to be quite different. As the blue-ish ultraviolet light hits the atmosphere it excites hydrogen atoms making them glow red. On Earth we see something similar, except that in our atmosphere of nitrogen and oxygen, the dominant colours would be green and blue.

INTERVIEW

"These images in ultraviolet light capture Saturn's auroras as they change over a few days. Auroras are the result of charged space particles colliding with the planet's magnetic field, leading to flashes produced by gas in its atmosphere. The emission is in the form of radio waves and ultraviolet light. An increase in the intensity of the emission is accompanied the emission ring shrinking. This particular behaviour is different from those observed in the auroras of both the Earth and Jupiter."

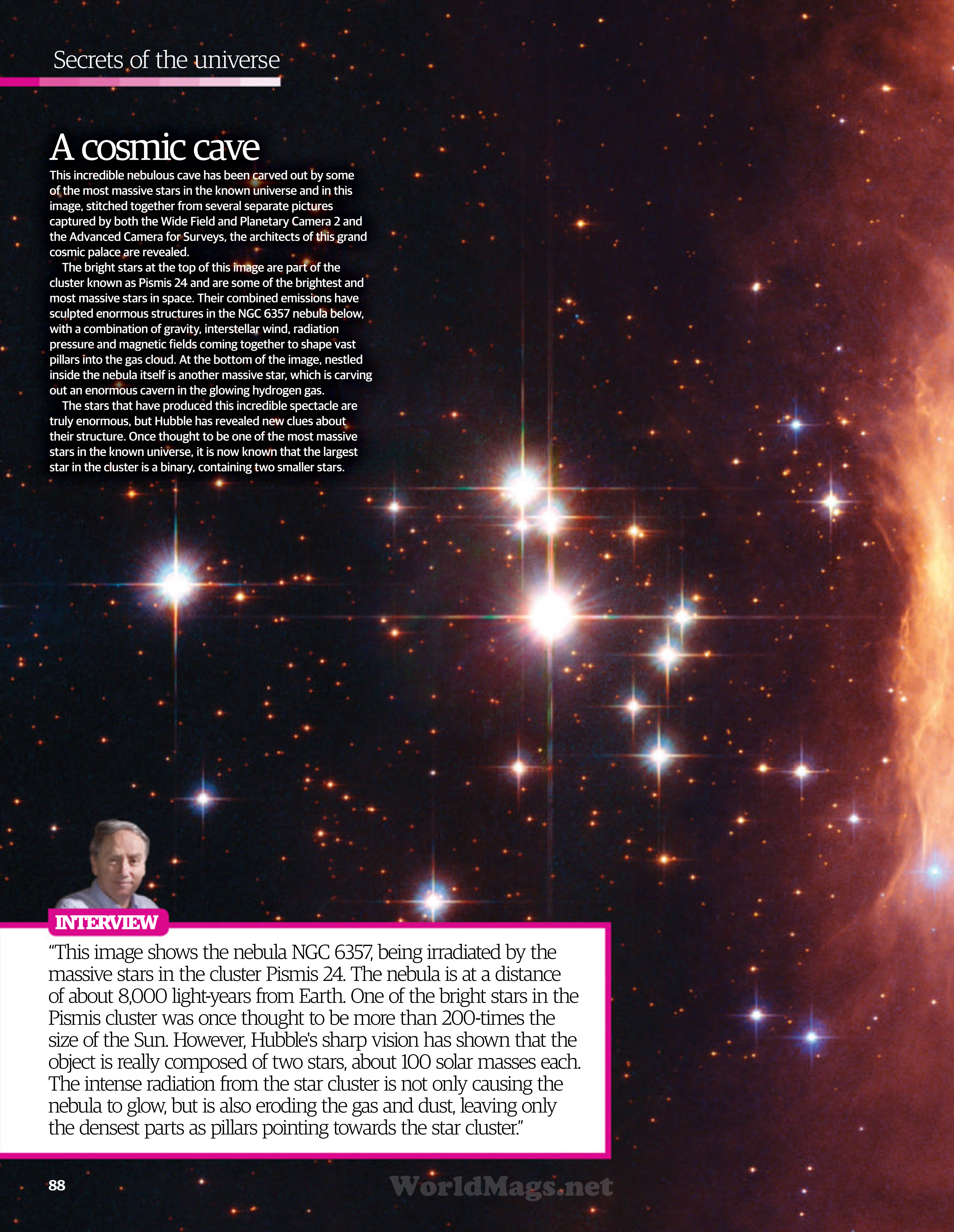
Jupiter's stormy spots

Hubble's Wide Field Planetary Camera 2 has trained its eye on Jupiter, watching carefully as storms rage across the equator. The enormous storm that is Jupiter's Great Red Spot has achieved worldwide fame, persisting in the Jovian atmosphere for 200 to 350 years, but it is not alone. This image captured in 2008 shows its two smaller companions. The largest, Red Spot Jr. was discovered in 2006, but the third, dubbed Baby Red Spot was new. They both started life as white spots and turned red as material was lifted high above the methane atmosphere, exposing it to ultraviolet light. Shortly after this image was taken Hubble watched as Baby Red Spot became caught up in the vortex of its big brother and was gone, providing a potential explanation as to how the great storm continues to gather momentum even after all this time. Since it was first measured by the Voyager spacecraft in the 1970s, the Great Red Spot has shrunk dramatically and Hubble's newer Wide Field Camera 3 continues to keep watch.

Comets, stars and galaxies

The star of this image isn't actually a star, but the streaking comet ISON, snapped by Hubble as it made its final journey towards the Sun. As it travelled inwards the temperature rose, leaving a tail of evaporating material in its wake. ISON was known as a sungrazing comet and in December 2013 it broke apart as it faced searing heat and came within 1.9 million kilometres (1.2 million miles of the surface of the Sun.

At first glance, the background appears to be studded with stars, but a closer look reveals a sea of galaxies. Captured by the Wide Field Camera 3, this incredible image is a combination of separate exposures and Hubble reveals an amazing contrast of depth. The comet was just a few hundred million miles from the Earth, the nearest stars in the picture are 60,000-times more distant and the closest galaxies are more than 30 billion-times farther away.



A cosmic cave

This incredible nebulous cave has been carved out by some of the most massive stars in the known universe and in this image, stitched together from several separate pictures captured by both the Wide Field and Planetary Camera 2 and the Advanced Camera for Surveys, the architects of this grand cosmic palace are revealed.

The bright stars at the top of this image are part of the cluster known as Pismis 24 and are some of the brightest and most massive stars in space. Their combined emissions have sculpted enormous structures in the NGC 6357 nebula below, with a combination of gravity, interstellar wind, radiation pressure and magnetic fields coming together to shape vast pillars into the gas cloud. At the bottom of the image, nestled inside the nebula itself is another massive star, which is carving out an enormous cavern in the glowing hydrogen gas.

The stars that have produced this incredible spectacle are truly enormous, but Hubble has revealed new clues about their structure. Once thought to be one of the most massive stars in the known universe, it is now known that the largest star in the cluster is a binary, containing two smaller stars.

INTERVIEW

"This image shows the nebula NGC 6357, being irradiated by the massive stars in the cluster Pismis 24. The nebula is at a distance of about 8,000 light-years from Earth. One of the bright stars in the Pismis cluster was once thought to be more than 200-times the size of the Sun. However, Hubble's sharp vision has shown that the object is really composed of two stars, about 100 solar masses each. The intense radiation from the star cluster is not only causing the nebula to glow, but is also eroding the gas and dust, leaving only the densest parts as pillars pointing towards the star cluster."

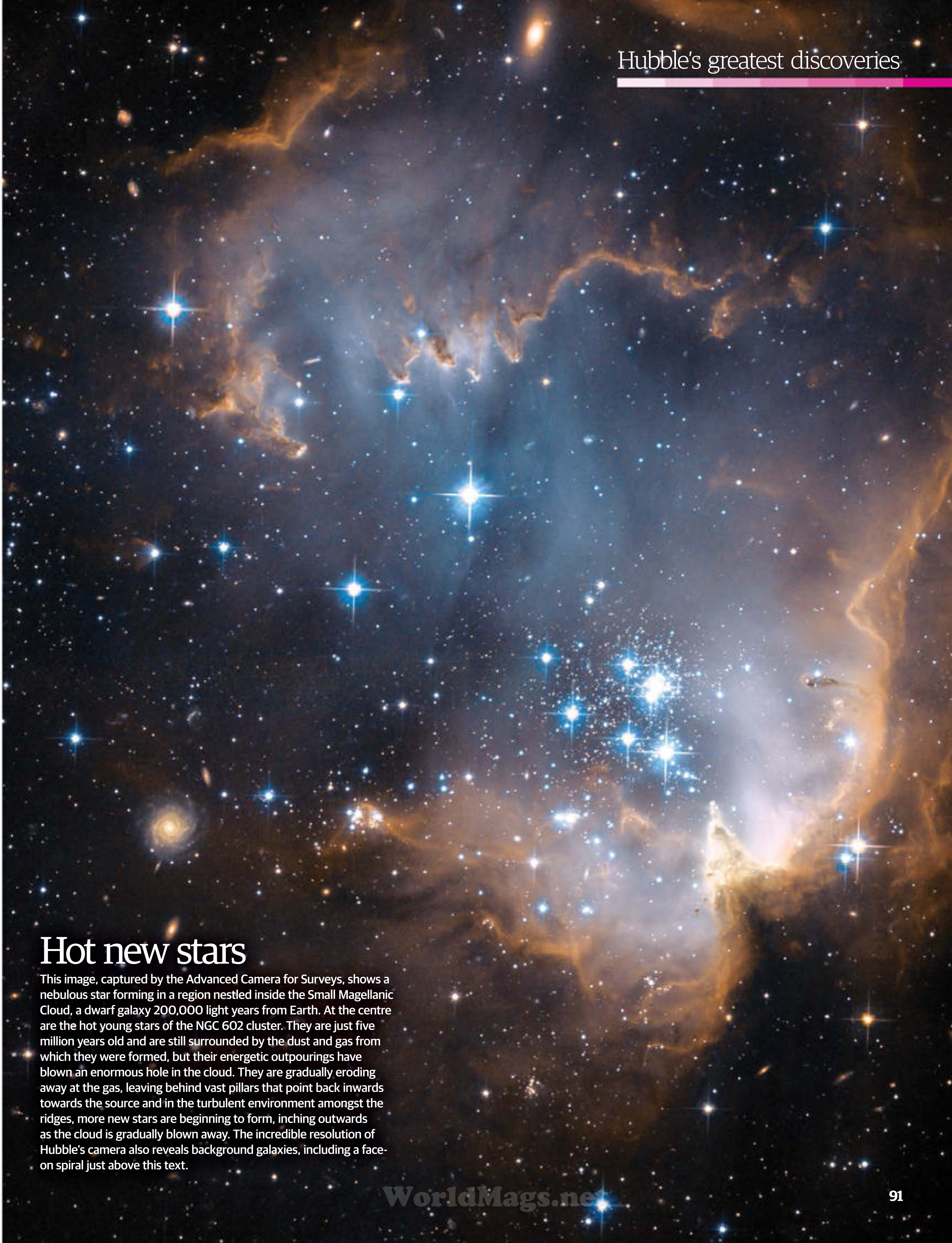
The perfect spiral

This incredible image of the spiral galaxy M74 is a combination of data captured over two separate years by The Advanced Camera for Surveys and has been combined with images captured by two ground-based telescopes to create a high-resolution view of the structure of a spiral galaxy. From our position on Earth, M74 is visible almost head on, creating an incredible portrait of the intricate swirls that make up spiral galaxies like our own, albeit on a smaller scale.

M74 is an almost perfect two-armed spiral, with dark dust lanes twisting outwards from its nucleus. Filters used on the camera reveal blue, visible and infrared light, highlighting chains of bright young stars that adorn its edges. Hubble has also picked out pockets of irradiated hydrogen gas, glowing pink as the ultraviolet light emitted by these hot young stars excites the molecules, providing an ideal environment for star formation.

INTERVIEW

"The galaxy M74 is at a distance of about 32 million light years from Earth and contains about 100 billion stars. It is a spiral galaxy, which means that its structure is that of a pancake-like flat disc. We are viewing the galaxy face-on, so that the spiral structure, which is a consequence of density waves in the galactic disc, is beautifully visible. New stars are being born in the spiral arms and they heat up the gas and cause it to glow. Three exploding stars, known as supernovae, have been detected in M74. One in 2002, one in 2003 and one in 2013."



Hot new stars

This image, captured by the Advanced Camera for Surveys, shows a nebulous star forming in a region nestled inside the Small Magellanic Cloud, a dwarf galaxy 200,000 light years from Earth. At the centre are the hot young stars of the NGC 602 cluster. They are just five million years old and are still surrounded by the dust and gas from which they were formed, but their energetic outpourings have blown an enormous hole in the cloud. They are gradually eroding away at the gas, leaving behind vast pillars that point back inwards towards the source and in the turbulent environment amongst the ridges, more new stars are beginning to form, inching outwards as the cloud is gradually blown away. The incredible resolution of Hubble's camera also reveals background galaxies, including a face-on spiral just above this text.

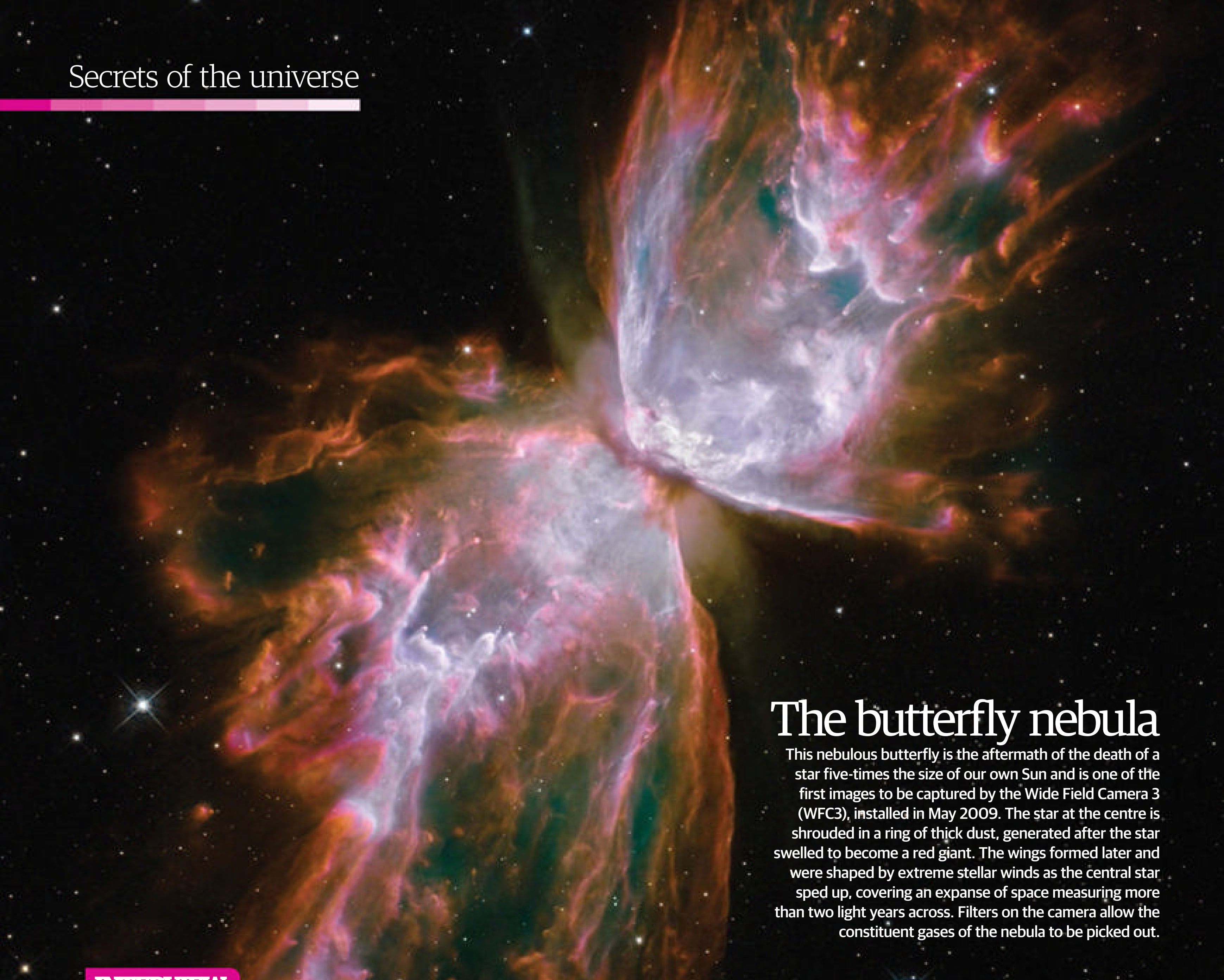
The centre of the galaxy

In 2008, Hubble teamed up with the Spitzer Space Telescope to peer right into the centre of the Milky Way. In the process it orbited the Earth 144 times and made 2,304 separate exposures that were stitched together to build this stunning mosaic. Hubble's Near Infrared Camera and Multi-Object Spectrometer (NICMOS) were able to reveal objects around 20-times the size of our Solar System, producing the sharpest infrared image ever made of the core of the Milky Way. It revealed massive stars spewing strong stellar winds, sculpting the surrounding gas and showed the glow from ionised hydrogen in the vicinity. The image was laid over a colour survey, completed by the Infrared Array Camera on board the Spitzer Space Telescope, which although only about one tenth of the resolution of Hubble's image, separates the different wavelengths of infrared light by colour.

A delicate spiral

This delicate spiral galaxy is just 46 million light years away and was captured by Hubble's Wide Field Camera 3 (WFC3) in 2010. Four different filters were used to reveal its composition. At the centre is a yellow-white nucleus, lit by the glow of middle-aged stars and surrounding them are tight, delicate spirals composed of dark dust lanes studded with younger blue star clusters.

NGC 2841 is a massive spiral galaxy and at 150,000 light years in diameter is larger than the Milky Way, but star formation within the delicate spirals has slowed. The energetic youngsters have blown most of the surrounding gas away, halting new star birth in their immediate vicinity. Pockets of pink star forming regions are still visible but overall this delicate looking galaxy is relatively quiet compared to other spirals like our own.



The butterfly nebula

This nebulous butterfly is the aftermath of the death of a star five-times the size of our own Sun and is one of the first images to be captured by the Wide Field Camera 3 (WFC3), installed in May 2009. The star at the centre is shrouded in a ring of thick dust, generated after the star swelled to become a red giant. The wings formed later and were shaped by extreme stellar winds as the central star sped up, covering an expanse of space measuring more than two light years across. Filters on the camera allow the constituent gases of the nebula to be picked out.

INTERVIEW

"I am certainly proud to have been a part of this fantastic scientific endeavour"

How did you get involved with Hubble?
Shortly after its launch in 1990, I was contacted by a colleague that was already at the Space Telescope Science Institute (the institute that conducts the scientific program of Hubble) and he asked me whether I would consider coming to work at the Institute. I had visited it already in 1986 and hence was somewhat familiar with the organisation and I knew quite a few of the astronomers there. So after a brief hesitation, I said I would definitely consider it.

Hubble got off to a shaky start: what was the feeling at the Space Telescope Science Institute when the flaw was discovered?
I was not yet at the Institute when the spherical aberration of the mirror was discovered, but I was absolutely shocked to hear about it. When I eventually decided to come to the Institute in 1991, a few of my colleagues were telling me that I must be crazy to come work with a flawed telescope. There was indeed a serious risk, since at that point we didn't know whether it could be corrected.

At the time, did you anticipate that Hubble would go on to be such a huge success?
Absolutely not. At that time I feared that Hubble may be remembered as one of the biggest scientific failures. And one that could potentially jeopardise the entire concept of big, ambitious science. There was the danger that people would use the Hubble example to argue that too complex scientific missions are doomed to fail.

How did the mood change after it was fixed?
One can hardly describe it. The feeling of elation was similar perhaps to that felt after the birth of a new child. The drama added, of course, to the iconic status of this

Pillars of creation

Found within the famous Eagle Nebula, some astronomers think this cosmic cloud has already been blown away by a nearby supernova. But, because of its distance from Earth (7,000 light years), we won't see this for another 1,000 years.

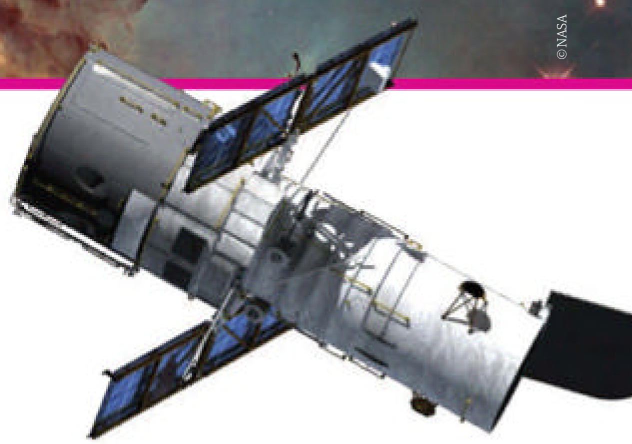
© NASA

telescope. This was an amazing demonstration of what can be achieved through the ingenuity of scientists and engineers and the courage of astronauts.

What do you think is the most iconic image captured by Hubble and which one is your personal favourite?
There is little doubt that the Eagle Nebula is Hubble's most iconic image. We have re-observed that region this year in high definition as part of the 25th anniversary celebrations. The new image is breathtaking. I personally like very much the image we call 'Mystic Mountain', which also shows pillars of gas and dust in which new stars are being born.

What were you hoping to see in the Hubble Deep Field images?
The various Hubble Deep Fields have not only shown us the universe at its infancy, when it was less that 500 million years old, while its current age is 13.8 billion years, they have also given us the cosmic history. For instance, we now know the rate at which the universe as a whole has been forming new stars, throughout its entire history. By showing us thousands of galaxies in an area of the sky similar to that you would see through a drinking straw, the Deep Fields have visually demonstrated to us the smallness of our physical existence, compared to the vastness of space. No one knew exactly what to expect from the Deep Fields, but they turned out to be a demonstration of cosmic archaeology at its best.

What is it about Hubble that has captured the public imagination?
A few elements have combined to make Hubble almost unique in the history of science. Hubble has brought the excitement of discovery, which used to be the province of only scientists, into the homes of people all across the globe. The drama that was associated with the flaw in the mirror and its spectacular repair has also added to Hubble's popularity - this was the 'telescope that could'. The incredible servicing missions by shuttle astronauts also captured the imagination. Hubble's longevity, 25 years of outstanding scientific results and the unbelievable images, some of which have been dubbed by an art writer as "the most remarkable works of art of our time.



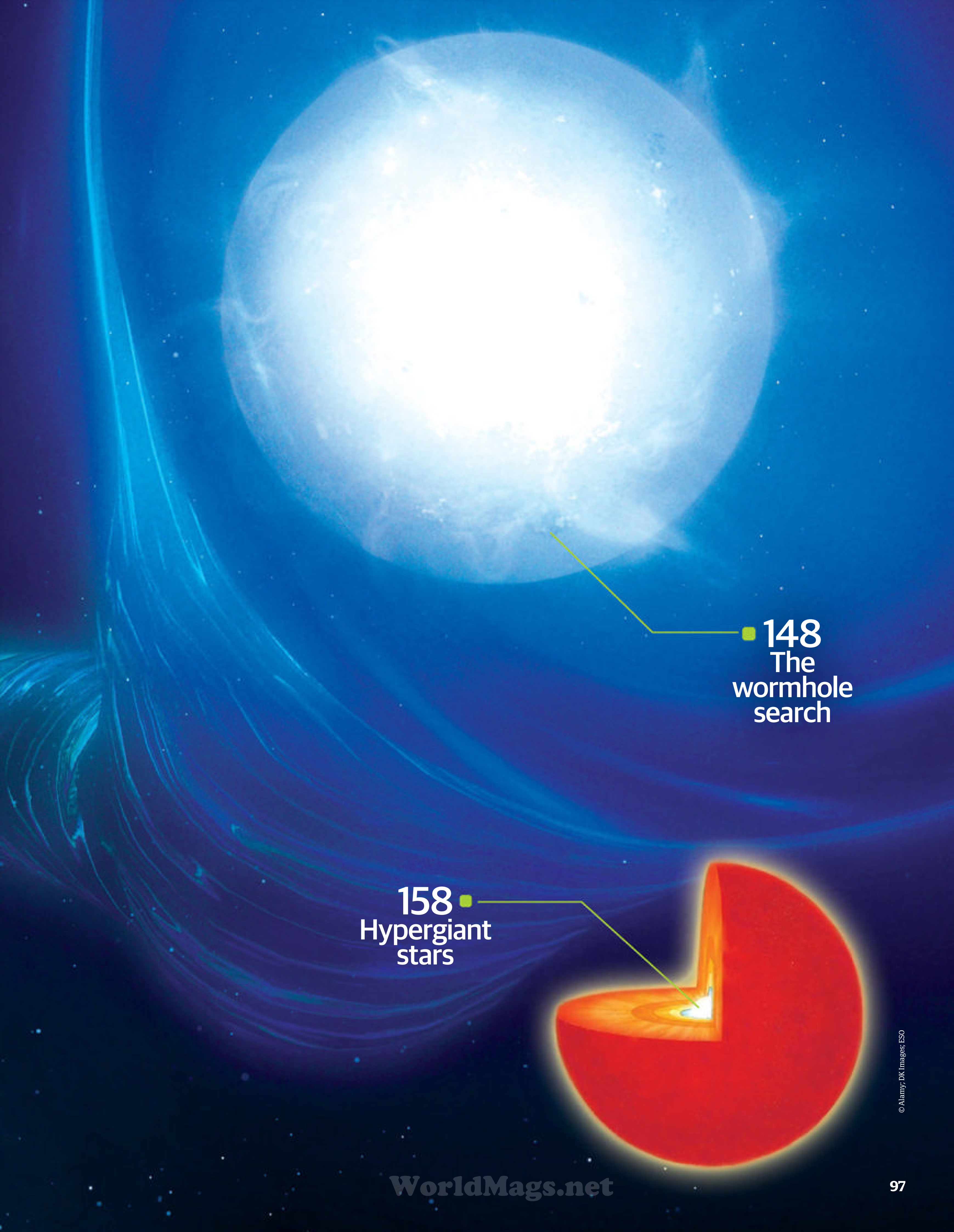
What does the future look like for Hubble?
We hope very much that Hubble will continue to operate at least till 2020, which will allow it a few years of overlap with the James Webb Space Telescope. If the telescope will still be scientifically productive at 2020, I hope that it will be kept even beyond that. Eventually, a propulsion module will be attached to the telescope, directing it into the ocean. However, I am convinced that Hubble will still make important discoveries in the coming years. I am certainly proud to have been a part of this fantastic scientific endeavour.

Science of the universe

The pieces that make up our universe

130 Super galaxies

"Astronomers have detected huge bursts of gamma-ray radiation from flashes of lightening around a black hole"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The wormhole search
158
Hypergiant stars
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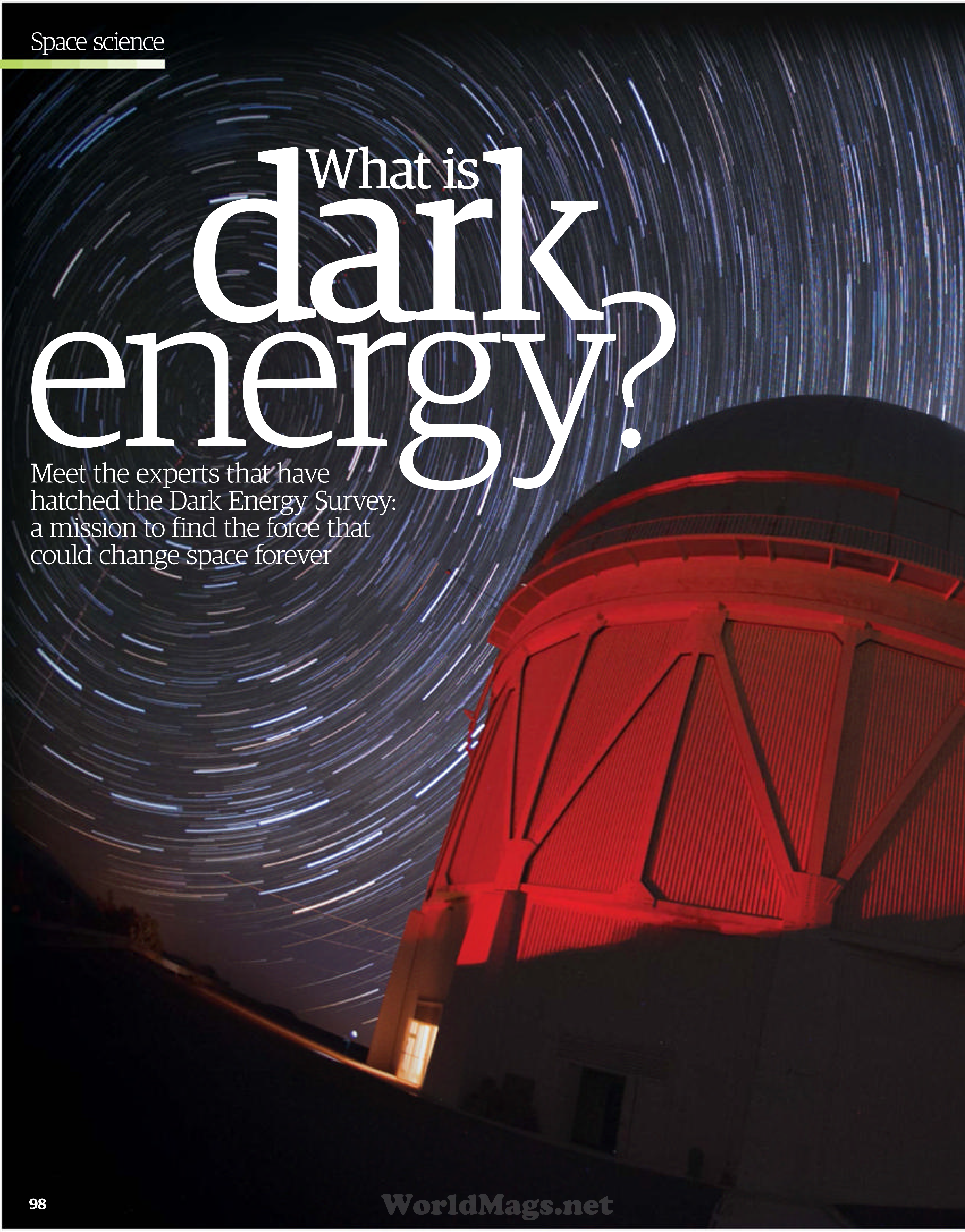


What is dark energy?

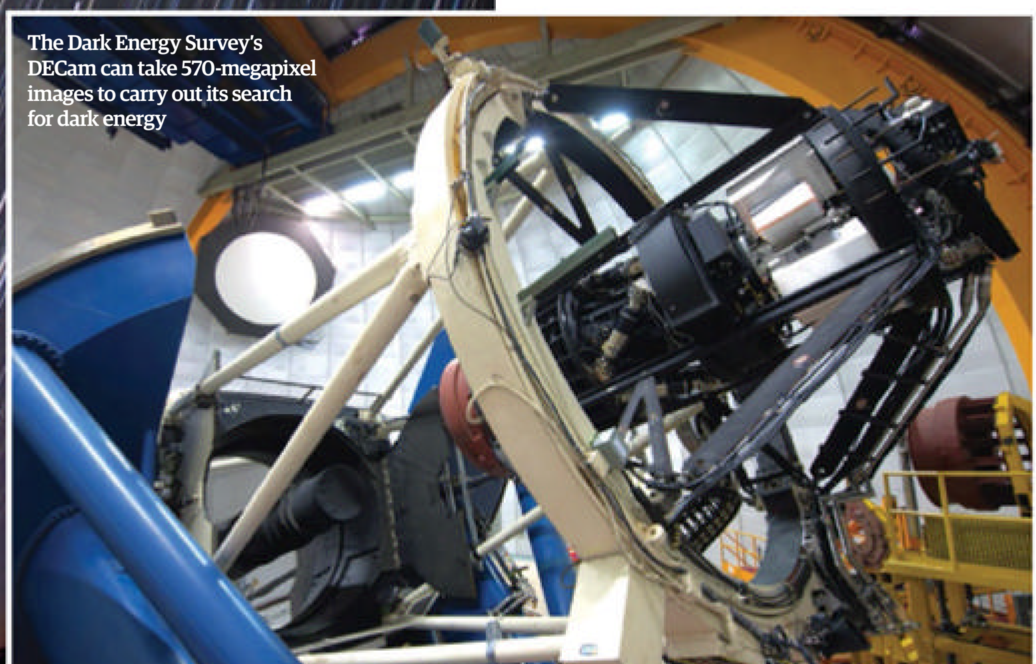
Meet the experts that have hatched the Dark Energy Survey: a mission to find the force that could change space forever

What is dark energy?

It seeps through every pore of the universe; an energy that permeates through anything and everything that stands in its way. Yet while it seems to be everywhere, this 'dark energy' almost behaves like some mythical beast that even our best equipment fails to catch. This mystery force seems to be pushing the galaxies that pepper the cosmos further and further apart, driving the very expansion of time and space from the moment everything that we know popped into existence.

Importantly, it is causing this expansion to accelerate, with the universe expanding at an ever faster rate rather than a decreasing rate, which is counter-intuitive given the fact that the Big Bang was 13.8 billion years ago. Dark energy could even decide the fate of the universe; if it keeps up then within 3 trillion years all the other galaxies in the universe will have moved so far away from the Milky Way with the cosmic expansion that we won't be able to see them any more and the universe beyond our galaxy will be dark. If dark energy increases its grip on the universe, it could not only pull galaxies away from each other, but pull the fabric of space apart, right down to the level of atoms – a catastrophic 'Cosmic Rip'.

Extraordinarily, dark energy makes up an astonishing 68.3 per cent of all energy in the cosmos. We do not know what it is yet, though, we just know that it's there. After all, the supernovae and galaxies as well as the static that also fills the entire universe – the cosmic microwave background (CMB) radiation – are indicating as much. And it is in these places that astronomers have been looking for the energy that has eluded them for so long. However, with clues come questions and these are puzzles not to be taken lightly. What the universe is actually doing – its expansion speeding up – is causing a tug of war between reality and Einstein's theory of general relativity. The pair refuse to agree – according to Albert Einstein, the father of physics' rules, gravity should be slowing everything down. With that in mind, we need to get to the energy that's throwing



The Dark Energy Survey's DECam can take 570-megapixel images to carry out its search for dark energy

what we believe into disarray – we need to probe the universe that's moving away from us in order to uncover dark energy's true nature. And we need to use the objects in it to do it.

What astronomers are hoping will be their ace card is sitting high up in the Chilean Andes and has been affixed to the Blanco four-metre (13-foot) telescope at Cerro Tololo Inter-American Observatory – the DECam, a highly sensitive dark energy camera that's carrying out the Dark Energy Survey, or DES, for short.

As of September 2012, the Dark Energy Survey is the new kid on the block when it comes to attempting to unravel dark energy – joining forces with Antarctica's South Pole Telescope, the Sloan Digital Sky Survey (SDSS) at Apache Point Observatory in New Mexico and the Vista Hemisphere Survey of ESO's Cerro Paranal Observatory in Chile. And, with well over 100 cosmologists from 23 institutions from the likes of the United Kingdom, Spain, Brazil and the United States backing the survey, there can be no doubt that it certainly means business.

The DECam – the powerhouse behind the Dark Energy Survey, is a master of all trades when it comes to searching for its quarry. Ensuring that it doesn't miss a thing, its multi-talented pixels don't just focus on one clue to dark energy's existence, its skill-set allows it to partake in multiple areas – namely the supernovae, galaxies and cosmic background radiation among which lurk clues to dark energy's nature. And to be successful in such a feat, the scientists behind DECam have ensured that the digital camera – which would dwarf your handheld at home – hasn't gone in unarmed. With 570 megapixels allowing it to peer great distances into space in a large swathe of the southern sky, DECam will try to uncover who will remain victorious in one of the biggest battles of the universe – its headlong expansion or the theory of general relativity – by snapping a map of its chosen area of sky in unprecedented detail.

And the world's most powerful digital camera gets to work as soon as the Sun sinks below the horizon, with the intention of turning its gleaming eye skyward for hundreds of nights over the next four to five years.

"We're looking at this big galaxy map of the universe as a way of finding evidence for dark energy and characterising its nature with cosmic epoch," says the head of the Dark Energy Survey Science Committee, Ofer Lahav of University College London. "An even more challenging goal for the Dark Energy Survey is to tell if what causes the acceleration of the universe is indeed dark energy."

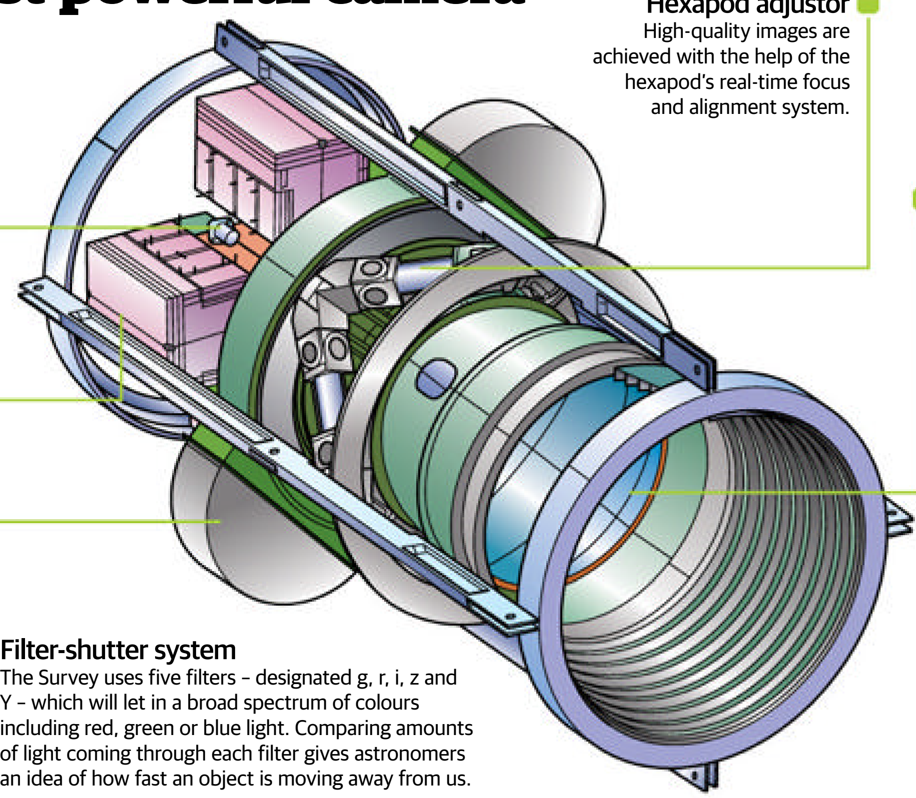
When the discovery of dark energy was announced in the late-Nineties, it came as a shock to scientists concerned with the expansion of the universe. Astronomers knew that the cosmos was expanding after the Big Bang, but they thought that after nearly 14 billion years it would be slowing down. But they wanted to know the rate at which it was slowing down, as this could be crucial for the future of the universe. So two teams of astronomers, one led by Saul Perlmutter and the other by Brian Schmidt and Adam Riess, set about trying to measure the expansion rate using a particular type of supernova.

The class of supernova that they were interested in were those belonging to the Type Ia category; two stars that were previously in an eternal tango where a dead star, dubbed a white dwarf, greedily grabs material from its larger, and more massive, companion. Over time, the stellar remnant bites off more than it can chew, and it begins to sweat under the amount of material that it has pulled onto itself before hitting the limit that causes an almighty explosion; the supernova that lights the way in finding more out about dark energy.

What is special about these Type Ia supernovae is that they always have the same natural brightness because the limit at which the white dwarf explodes is always the same mass, 1.4 times the mass of our Sun. This makes them ideal standard candles, which are like constant, identical beacons that light the way in the universe, like distance markers. If you know how bright the supernovae naturally are, then compare them to how bright or faint they appear to us on the sky, you can judge how far away they must be relative to one another.

> "We're looking at this big galaxy map of the universe as a way of finding evidence for dark energy" **Ofer Lahav**

World's most powerful camera



570-megapixel CCD
Using CCDs that are around ten times thicker than conventional ones, DECam doesn't just have the ability to view large areas of sky but it's also sensitive to red light from distant galaxies.

Readout electronics
An entire digital image can be read out and recorded in 17 seconds flat. Such a short time allows the camera to be read out in the time it takes the Blanco four-metre telescope to move to its next section of sky.

Filter-shutter system
The Survey uses five filters – designated g, r, i, z and Y – which will let in a broad spectrum of colours including red, green or blue light. Comparing amounts of light coming through each filter gives astronomers an idea of how fast an object is moving away from us.

Hexapod adjustor
High-quality images are achieved with the help of the hexapod's real-time focus and alignment system.

Correcting lenses
With the biggest of five Wynne-style lenses measuring 98cm (39in) in diameter and weighing in at 172kg (380lb), the optical corrector system provides a 2.2-degree field of view while not needing to contribute too much to the image's quality.

Interview

The supernova snapper

Prof Bob Nichol,
University of Portsmouth

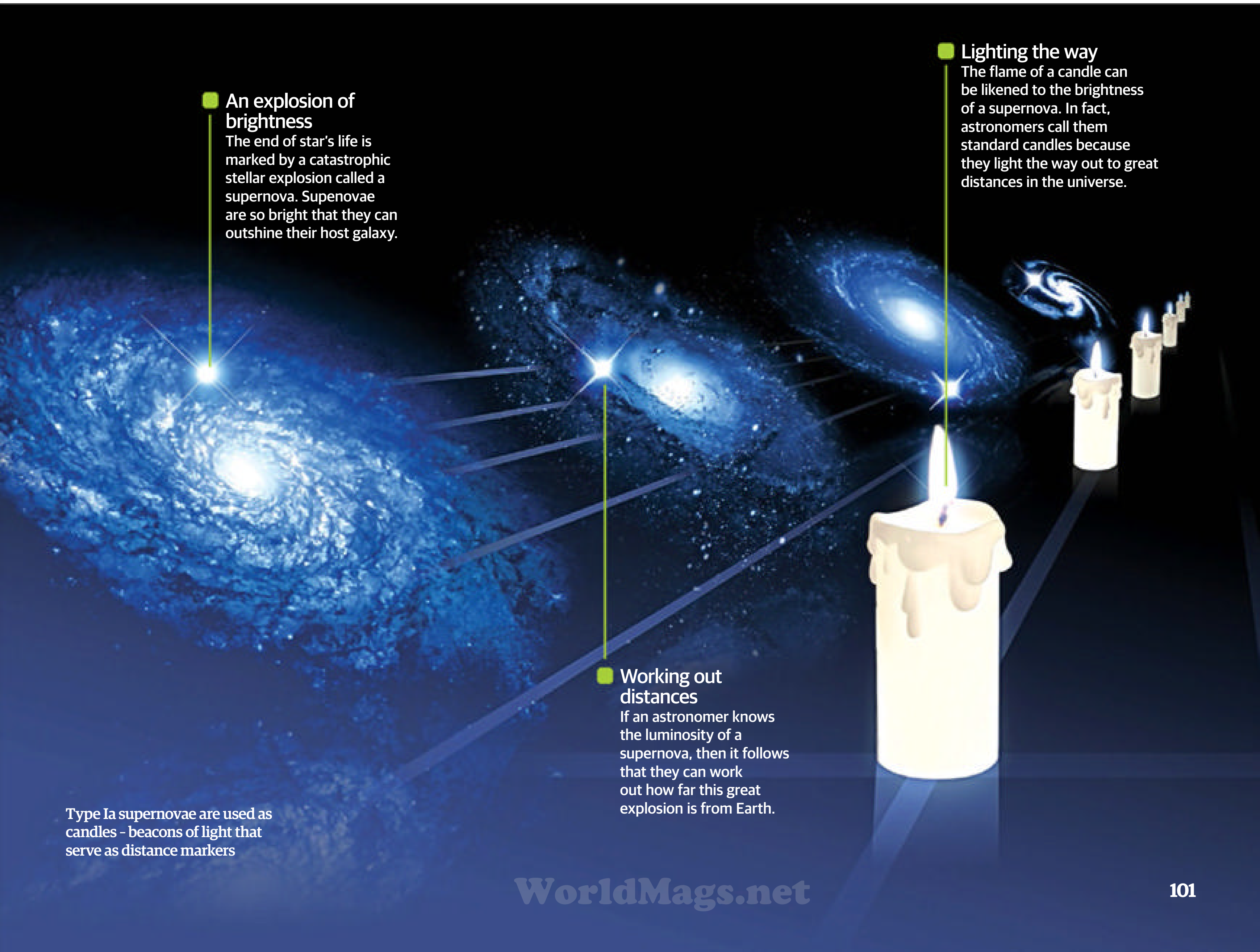
How can DECam pick up light from distant supernovae and turn this data into information about dark energy?
A Type Ia supernova is the total annihilation of a carbon-oxygen white dwarf star, turning all the mass into light. Since we know how much mass is roughly present, we can predict how bright it should be. This means we can use them as 'standardisable candles', which means we can manipulate them so they all have the same brightness at the peak of their explosion. Once we know their peak brightness, we can estimate their distance, which in turn allows us to determine how distance has changed with time.

Astronomers have about 1,000 Type Ia supernovae they can use to measure distances in the universe, but it is time to collect more supernovae, and better ones as well. DECam is ideal for this because it has a bigger field of view and has better detectors allowing us to see deeper into space. We find supernovae by taking a picture of the same part of the sky every few days. Supernova explosions change with time, so we look for anything that starts getting brighter with time, peaks, and then fades.

How confident are we that dark energy is the force behind the expansion of the universe?
I'm 100 per cent sure about the accelerated expansion of the universe. What causes that is another matter. Dark energy is one explanation and probably the most popular but we are no closer to understanding what dark energy could be.

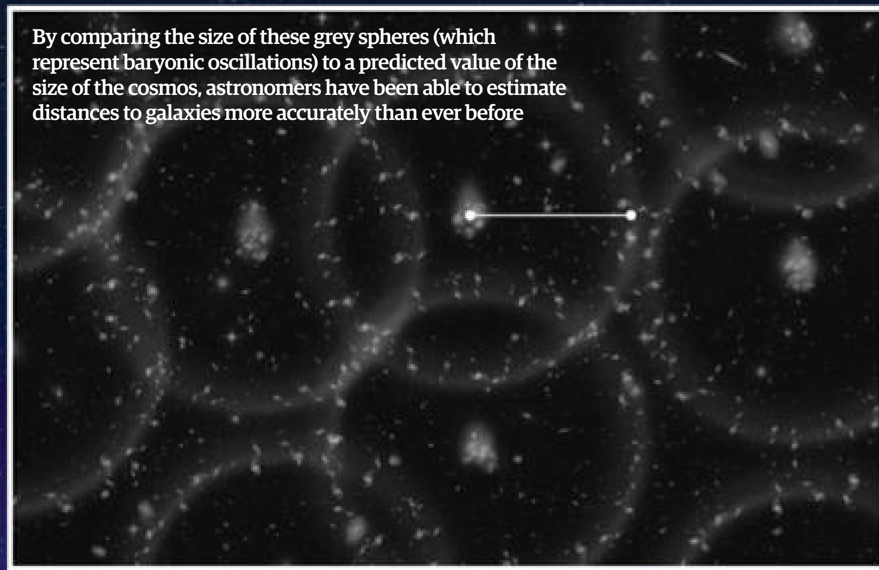
What are the problems that you face when using DECam to look at supernovae?
The main problem is classifying the supernova event once we've found it. It needs to be a Type Ia to allow it to be used to measure distances. Unfortunately this classification has previously been achieved by taking a spectrum of the event and using that to find out what type it is. That isn't possible for all supernovae as there are too many. So, we have now developed a photometric method for characterising supernovae and recent work, done at Portsmouth, suggests we can control the contamination from other types to less than three per cent.

What has been achieved so far with DECam and the Dark Energy Survey?
We've obtained 100 nights of telescope time on the Anglo-Australian Telescope. This is essential to the success of the survey. We've also found our first 'superluminous supernova'. These are 1,000 times rarer than Type Ia supernovae and appear to be 100 times brighter than any other supernova event.

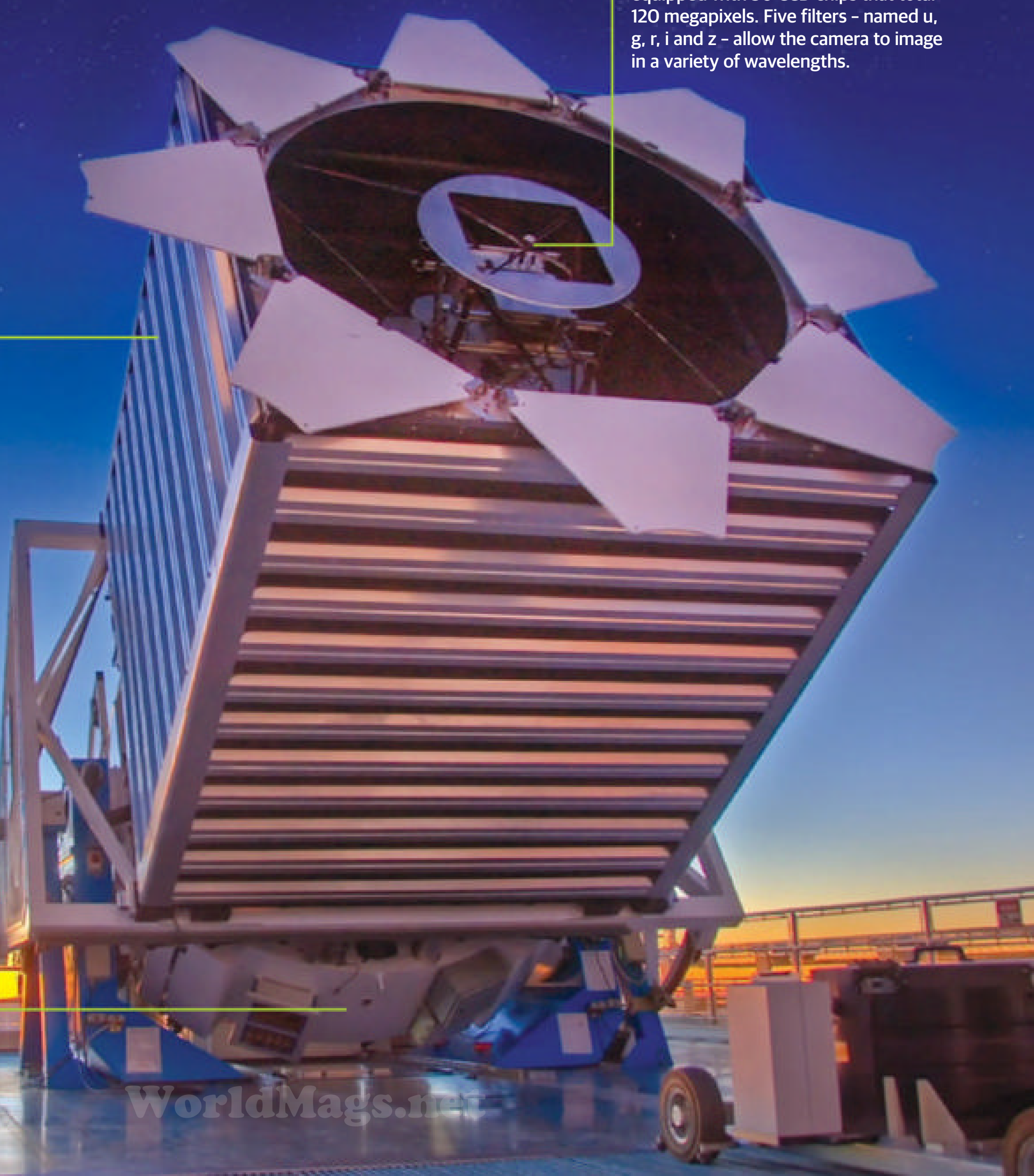


Type Ia supernovae are used as candles - beacons of light that serve as distance markers

Sloan Digital Sky Survey (SDSS)



By comparing the size of these grey spheres (which represent baryonic oscillations) to a predicted value of the size of the cosmos, astronomers have been able to estimate distances to galaxies more accurately than ever before



Wide-angle telescope

The Sloan Digital Sky Survey (SDSS) employs a 2.5m wide-angle optical telescope to carry out the Baryon Oscillation Spectroscopic Survey (BOSS) as part of the SDSS III project.

Multi-filter camera

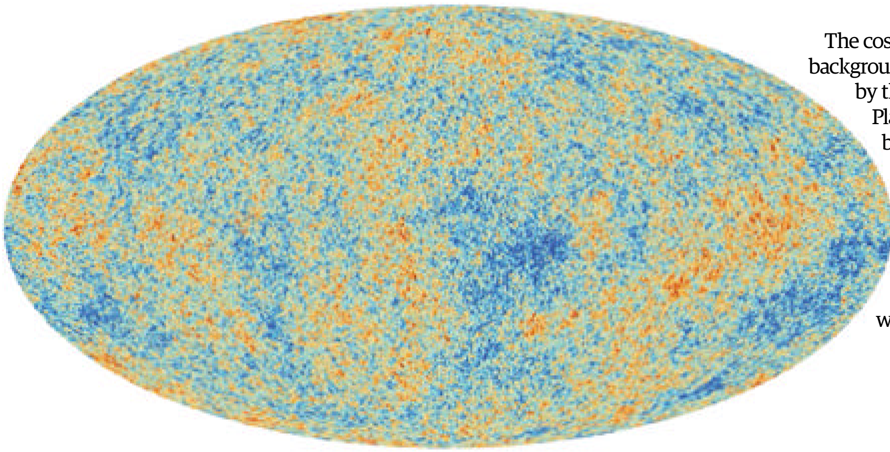
In its scanning of just over 35% of the sky, the telescope's camera is equipped with 30 CCD chips that total 120 megapixels. Five filters – named u, g, r, i and z – allow the camera to image in a variety of wavelengths.

Drift scanning

The telescope might remain locked into position, but that does not mean that it's not capable of scanning the sky. It makes use of the Earth's rotation to record small strips of its chosen region of sky.

What the two teams of astronomers found was astounding. They measured the redshifts of the supernovae, which told them how much their light had been stretched into redder wavelengths by the expansion of the universe and found that the supernovae were further away than they should have been if the expansion of the universe was indeed slowing down. The results could only mean that the expansion of the universe was not coming to a halt, but was instead speeding up. Nobody knew what could be causing this expansion, so they described this mysterious force as dark energy. Even though they didn't know what this dark energy was, the two competing teams who had raced to publish their results first and beat the other jointly won the Nobel Prize for their discovery. Today, supernovae are still hugely important for the same reasons and are one of the big aims of the DECam.

According to our current understanding, the early universe was alive with the sound of cosmic oscillations. One way the DECam will use to measure dark energy links the very distant, ancient universe with the cosmos that we can see around us today. After the Big Bang the universe was a seething soup of particles and things like galaxies and stars and planets hadn't formed yet. Huge pressure waves - essentially sound waves sweeping through the fog of matter in space - washed through this plasma soup, and on the crests of these waves the plasma was denser than in the troughs. As the universe cooled while it expanded, these waves were frozen in place and astronomers have found them hidden in the cosmic microwave background radiation emitted



The cosmic microwave background, as observed by the now defunct Planck Spacecraft back in 2013, is a snapshot of the oldest light in our universe, imprinted on the sky when the universe was just 370,000 years old

Collaborators of the Dark Energy Survey gather in front of DECam. Enrique Gaztañaga stands third from the right in the lower line with his team

Spanish DES scientists with the Blanco Telescope (left to right: Juan de Vicente, Laia Cardiel-Sas, Ramon Miquel, Juan García-Bellido, Enrique Gaztañaga and Francisco Castander)

Interview

Microwave listener

Dr Enrique Gaztañaga, professor of cosmology at the Instituto de Ciencias del Espacio

Where do the baryon acoustic oscillations, or BAOs, come from?

They come from the very early stages of the universe, when it was dominated by radiation. In general gravity tends to amplify small primordial density or energy perturbations: the more matter or energy, the stronger the gravitational force. Gravitational attraction is the basic mechanism behind the growth of structures in the universe (such as galaxies or stars). But at that early time radiation pressure opposed gravity and this generates oscillations very similar to sound waves or waves in the sea.

What aspects of dark energy can the BAOs tell us about?

In particular we want to measure what is the density of dark energy and how it evolves with time. This could shed new light over the nature of dark energy. In combination with other measurements, like the rate of growth of structure, which we can also do with DES, we will be able to decide if the dark energy model can fit the data or if we need instead to change the laws of physics, like the law of gravity on very large scales.

Why do we assume that dark energy is the driving force behind the universe's expansion?

With the BAO or supernova measurement alone, it will be hard to decide that dark energy is the driving force behind expansion. This is because there are many possible models for dark energy. But we will be able to at least rule out or confirm the simplest of these models: the cosmological constant [which is the strength of the raw energy present in space]. To understand the cause of the cosmic acceleration we need to combine the BAO and supernova results with measurements of the growth rate of structure in the universe. This is how fast density perturbations grow. We can do this in the Dark Energy Survey by measuring galaxy clustering, weak gravitational lensing and the abundance of galaxy clusters.

Have you uncovered anything important yet?

So far, the Dark Energy Survey has not taken enough data to measure BAO, but we are testing the other methods to measure the growth and preparing for the BAO analysis by studying systematic effects that might affect the BAO measurement once we have enough data.

Is measuring BAOs an easy measurement to make?

There are several effects that we need to take into account to make a good BAO measurement. Some are related with the quality of the data taken and its calibration. For example, we need to get rid of the foreground contamination from stars and dust in our galaxy, and also from the Earth's atmosphere or from instrument noise and damage (for example cosmic rays, satellite trails, scattered light). Some are related to the modelling of the observed BAO oscillations that are subject to other effects, such as non-linear gravitational evolution or biases between the light that we see and the true underlying mass that we do not see.

370,000 years after the Big Bang. Between then and now, the denser material in the crest of the waves gradually attracted more and more material, growing into galaxies, and clusters of galaxies and finally huge chains of galaxy clusters stretching hundreds of millions of light years in some cases. By doing huge surveys of faint galaxies astronomers can piece together maps of the universe that show where these huge chains that grew out of the waves are located. Astronomers have even run huge simulations on supercomputers that have described the evolution of the universe, showing the growth of these waves with voids in between them. Because of how these filaments look on the largest scale, scientists call it the 'cosmic web'.

So what is the connection? If the largest structures in the universe grew from these waves, which scientists technically call baryon acoustic oscillations, or BAOs, then the rate at which the universe has expanded will decide how large these structures have grown. In a way, they are like big cosmic 'rulers' by which to measure the universe, so astronomers called them 'standard rulers'. This is defined by the distance the waves travelled before they froze in place, which has been termed the 'sound horizon' and is the speed of sound multiplied by 370,000 years, which was the age of the universe when they froze. As the universe has expanded, the waves have grown to be around 450 million light years. What DECam will do is study chains of galaxy clusters that make up these waves during different ages in the universe, which is made possible because the further away you look in the universe, the further back in time you are looking. So DECam will be able to measure their growth at different stages in the universe and see how strong dark energy has been in the past compared to today.

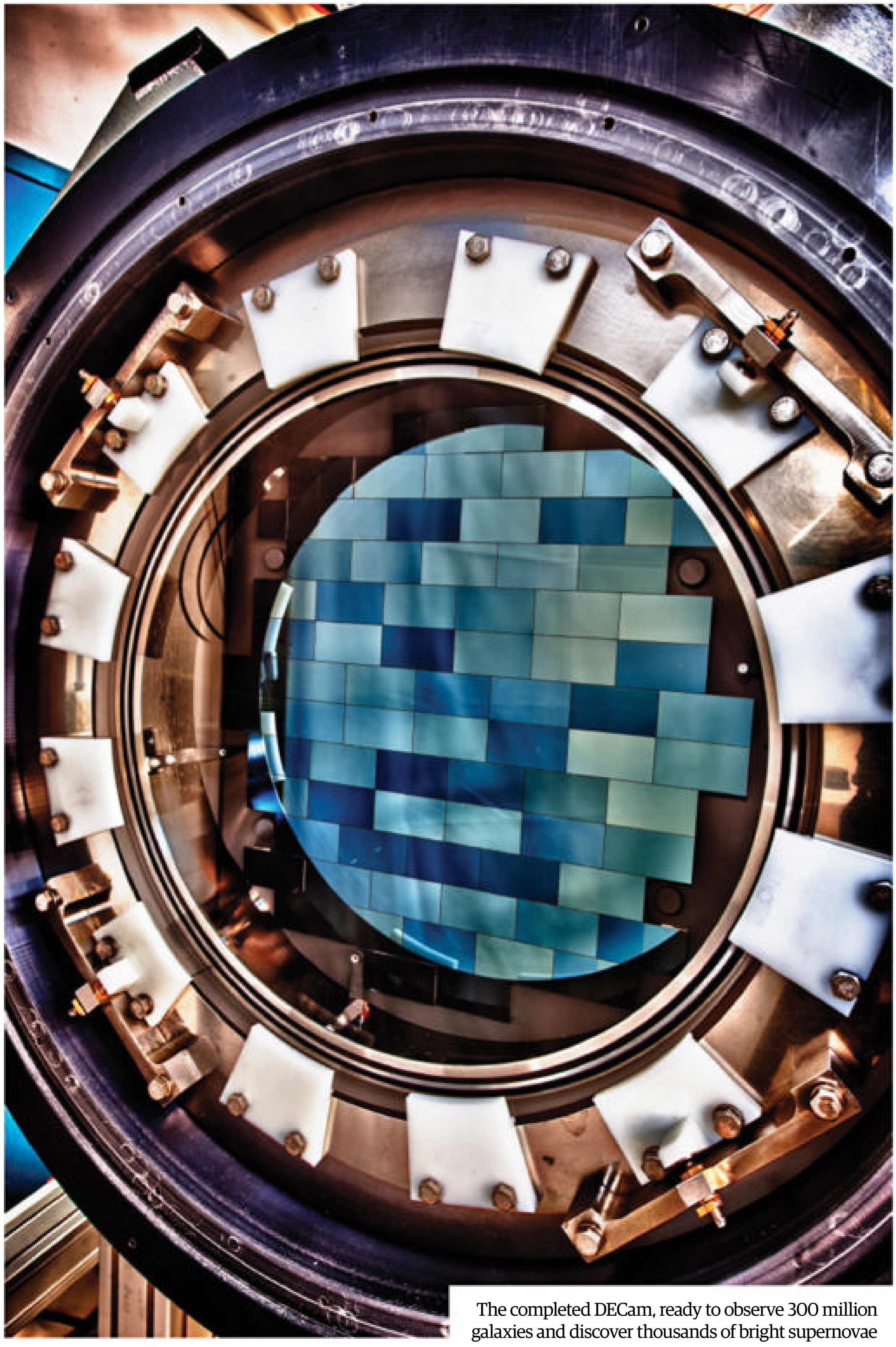
Over at Apache Point Observatory in New Mexico, one of DECam's partners in seeking out dark energy – the Sloan Foundation 2.5-metre Telescope's SDSS III – has also been busy taking advantage of these BAOs as part of its Baryon Oscillation Spectroscopic Survey (BOSS). Quite recently, the survey measured the distances to galaxies more than 6 billion light years away to an accuracy not ever achieved before, placing new constraints on the mysterious dark energy's properties.

What they found appears consistent with a form of dark energy that stays constant throughout the history of the universe. "We don't yet understand what dark energy is," explains astronomer Daniel Eisenstein, the director of the SDSS, "but we can measure its properties." Everywhere you look in the cosmos there are galaxies; those collections of stars held together by gravity to form the most majestic of structures. And gravity likes to bind them further, into huge collections of dozens, hundreds or even thousands of galaxies and we call these groups 'galaxy clusters'.

DECam is going to be spending time counting these clusters, going as far back as when the universe was less than half of its current size. But how will this help astronomers understand dark energy? Let's think about it: gravity is pulling galaxies together, but dark energy is working in the opposite direction to pull galaxies apart. So it is like a cosmic tug of war – can gravity win over dark energy, or will dark energy pull galaxies apart to limit how big clusters can grow?

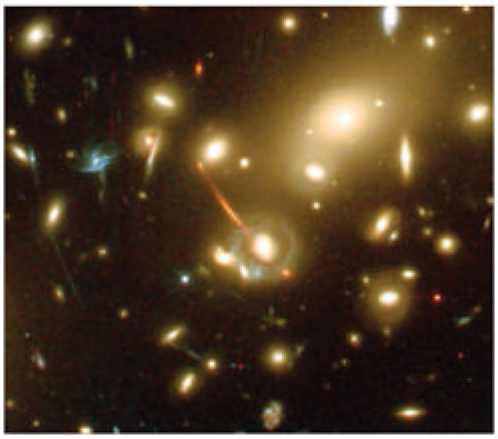
The idea is for DECam to survey galaxies at different eras in the universe and see how big they were and how fast they grew at different times. We know dark energy is winning the battle now because the expansion of the universe is accelerating, but in the past when the universe was smaller and everything was closer together, gravity had a much greater influence and was able to override the effect of dark energy. Plus astronomers would like to know if the strength of dark energy has been constant over history, or if it has changed. If its strength varies, then that has implications for the future because it would mean that the strength of dark energy could change again, affecting the evolution of the universe.

But just how can scientists measure the mass of galaxy clusters? With the help of advanced technology, of course. Working on their computers they have simulated what the masses of clusters should be based on what we know about the universe and dark energy, but we do not know for sure that they are those masses in reality. So what is DECam looking for? Their physical size is not



The completed DECam, ready to observe 300 million galaxies and discover thousands of bright supernovae

The South Pole Telescope in Antarctica teams up with DECam in the hunt for dark energy



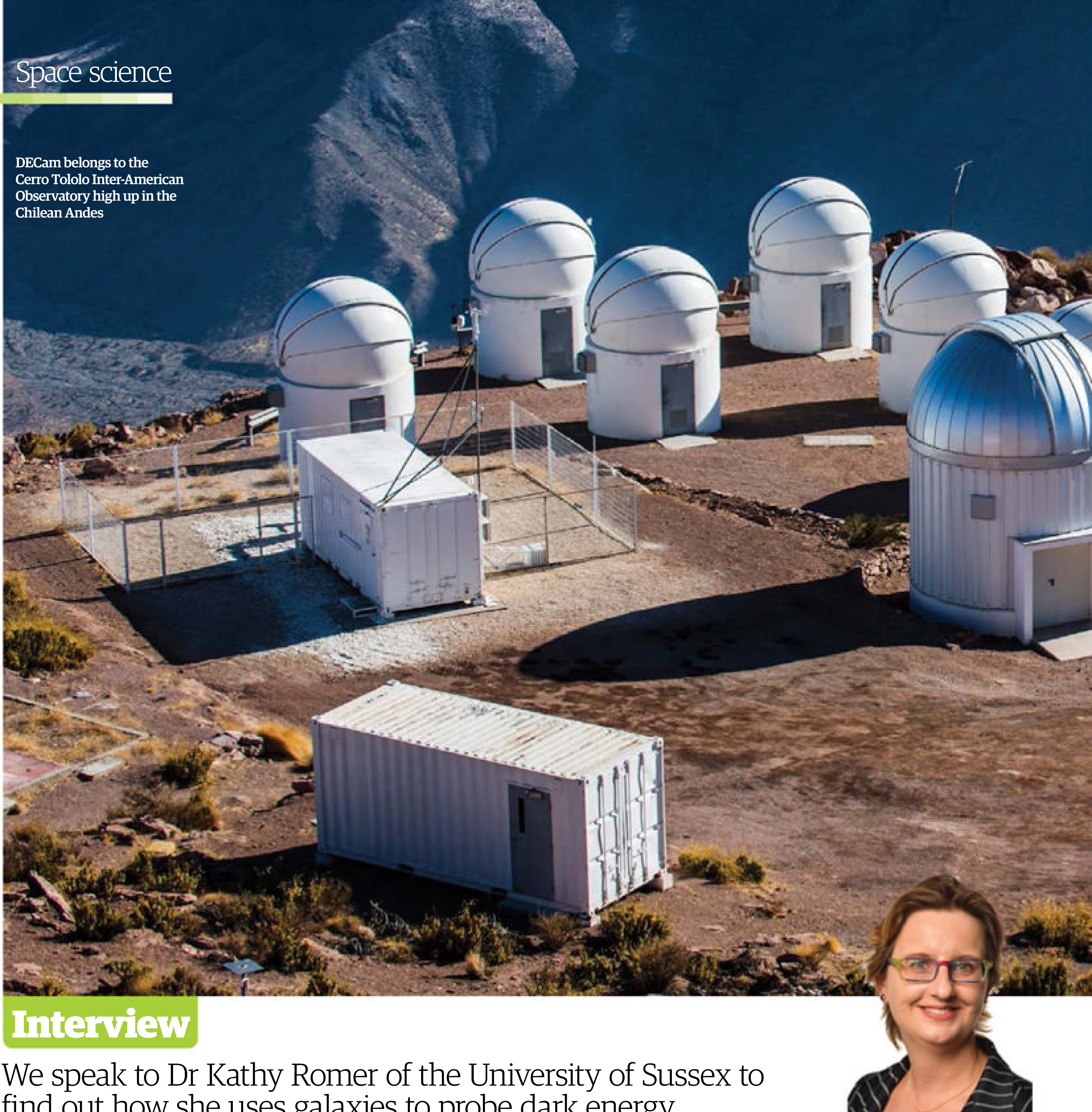
Gravitational lensing at work in the Abell 2218 cluster: distant, lensed galaxies appear stretched into arcs

necessarily a guide, because some clusters are more compact than others. Counting all of the galaxies in a cluster only gets astronomers so far too, because that doesn't account for two things: firstly, the hot gas filling the spaces between galaxies in a cluster that shines in X-rays and secondly, the ominous and invisible dark matter.

"We don't yet quite understand what dark energy is, but we can measure its properties" **Daniel Eisenstein**

The South Pole Telescope in Antarctica, which is possibly the most inhospitably located telescope on the planet, will study how the hot gas in clusters scatters photons from the cosmic microwave background radiation, which will give astronomers an indication of how much gas there is within a galaxy cluster. Meanwhile, the Blanco Telescope on which DECam is attached is going to search for an amazing phenomenon that was predicted by none other than Albert Einstein, which is gravitational lensing.

Think of a big lens in space that acts to magnify objects beyond it, such as galaxies. But how can space act as a lens? It can because objects warp space with their gravity, which depends on their mass, causing the path of light from objects beyond to bend. Sometimes the gravitational lens is obvious, causing galaxies to look much brighter, but the lens is imperfect and the images of the more distant galaxies appear warped or smeared or bent, or have multiple images of them made as their light takes different paths along warped space. The most perfect kind of gravitational lens is what's known as an Einstein ring – the light of the more distant object is warped into a complete ring around the nearer, lensing object. Other times the lensing effect is very subtle, just two per cent. Galaxy clusters make excellent gravitational lenses because they are so massive and, the heavier a galactic grouping, the more light is bent. DECam is able to measure these masses by looking at how big a lens a galaxy cluster makes, surveying 300 million individual galaxies in the process. Combining its ability to count and 'weigh' galaxy clusters, measure supernovae as well as build a map to chart the sounds of the universe, DECam, the most powerful survey instrument of its kind, seems to have all bases covered. However, whether it will be able to snag dark energy for all to observe, is something that only time will tell.



DECam belongs to the Cerro Tololo Inter-American Observatory high up in the Chilean Andes

Interview

We speak to Dr Kathy Romer of the University of Sussex to find out how she uses galaxies to probe dark energy

How important is the Dark Energy Survey to scientists' efforts to understand dark energy?
The Dark Energy Survey will use the DECam instrument to locate millions of galaxies across a large fraction of the southern sky. It will also locate thousands of exploding stars, known as supernovae. The galaxies and supernovae can be used as beacons to trace the size, shape and history of the universe. These are all properties that are modified by dark energy. Therefore, by comparing observations with theoretical predictions, we can get closer to knowing which theory of dark energy is correct.

The starlight from the galaxies we observe with DECam is up to 10 billion years old (the further away the galaxy, the older the light), so this experiment is a lot like an archaeological dig – we cannot influence what the galaxies do, but by examining them in detail, and in situ, we can learn a lot about the universe at the time the light was emitted.

Could dark energy have altered between the early universe and now?
In most models of dark energy, the dark energy changes its properties with time, although in only very few does it change its properties with location, ie you can think of dark energy as being uniform in space, but not in time, in those models. However, there is one very important exception, the dark energy model known as the 'cosmological constant' – this model was first proposed by Albert Einstein about a hundred years ago (and made decades before the accelerated expansion was detected).

In the cosmological constant model, the dark energy is uniform in both time and space. It is the simplest dark energy theory and also seems to be the one most favoured by current observations.

How does the South Pole Telescope team up with DES in the study of clusters of galaxies?
Clusters of galaxies are bright not only in the optical part of the spectrum (where DECam is sensitive), they can also be detected in the microwave part of

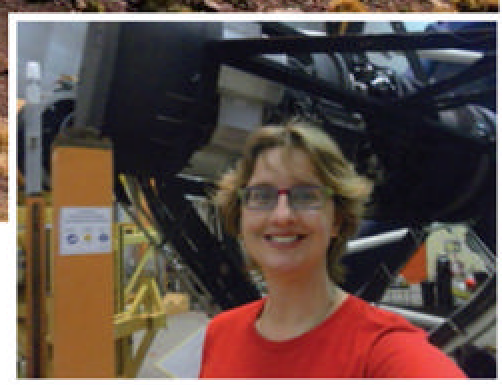
the spectrum (because they contain vast quantities of hot diffuse gas). Unlike almost everywhere else on the Earth, microwaves from clusters of galaxies can get all the way to the ground at the South Pole, because it is the driest place on Earth. At almost every other terrestrial location, microwaves from space are absorbed by water molecules in the atmosphere (by the same physics mechanism that allows you to heat up water in a microwave oven).

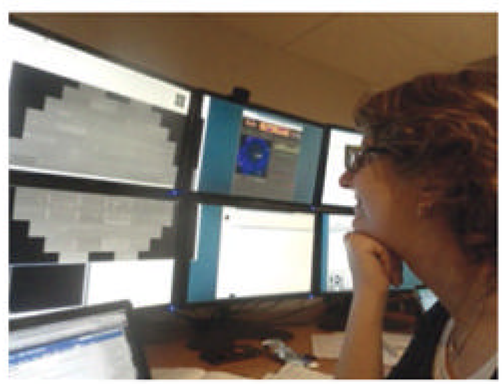
A large microwave telescope at the South Pole (the South Pole Telescope) has been scanning the sky to search for clusters of galaxies for the last few years. By combining galaxy data from DES and microwave data from the SPT we are able to measure masses of, and distances to, clusters much more accurately than we could do using the data separately.

What will happen if Einstein's theory of general relativity is proved to be insufficient or too simple in explaining cosmic acceleration?
Einstein's theory for gravity is appealing, and has been so popular for nearly a hundred years, because of its conceptual (if not mathematical!) simplicity. It is possible that it might be too simple, and some sophistication might need to be added based on future findings.

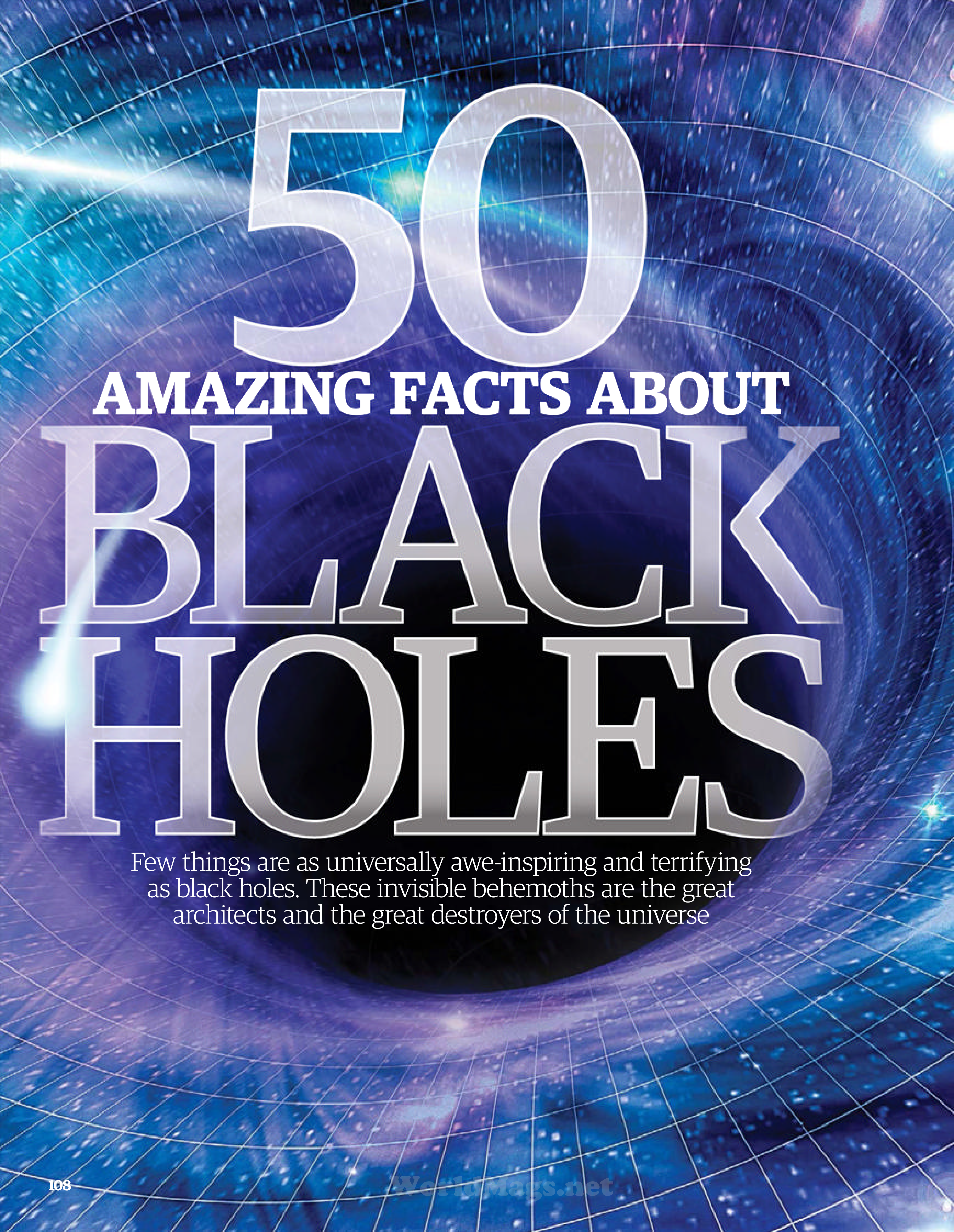
By doing so we won't need to radically change our theories for the universe's history, but it will change our predictions for our universe's future: an accelerated expansion has the unfortunate consequence of an eventual 'Cosmic Rip', whereas we might be in for a less cataclysmic future if gravity acts differently to our current assumptions.

"Supernovae can be used as beacons to trace the history of the universe"



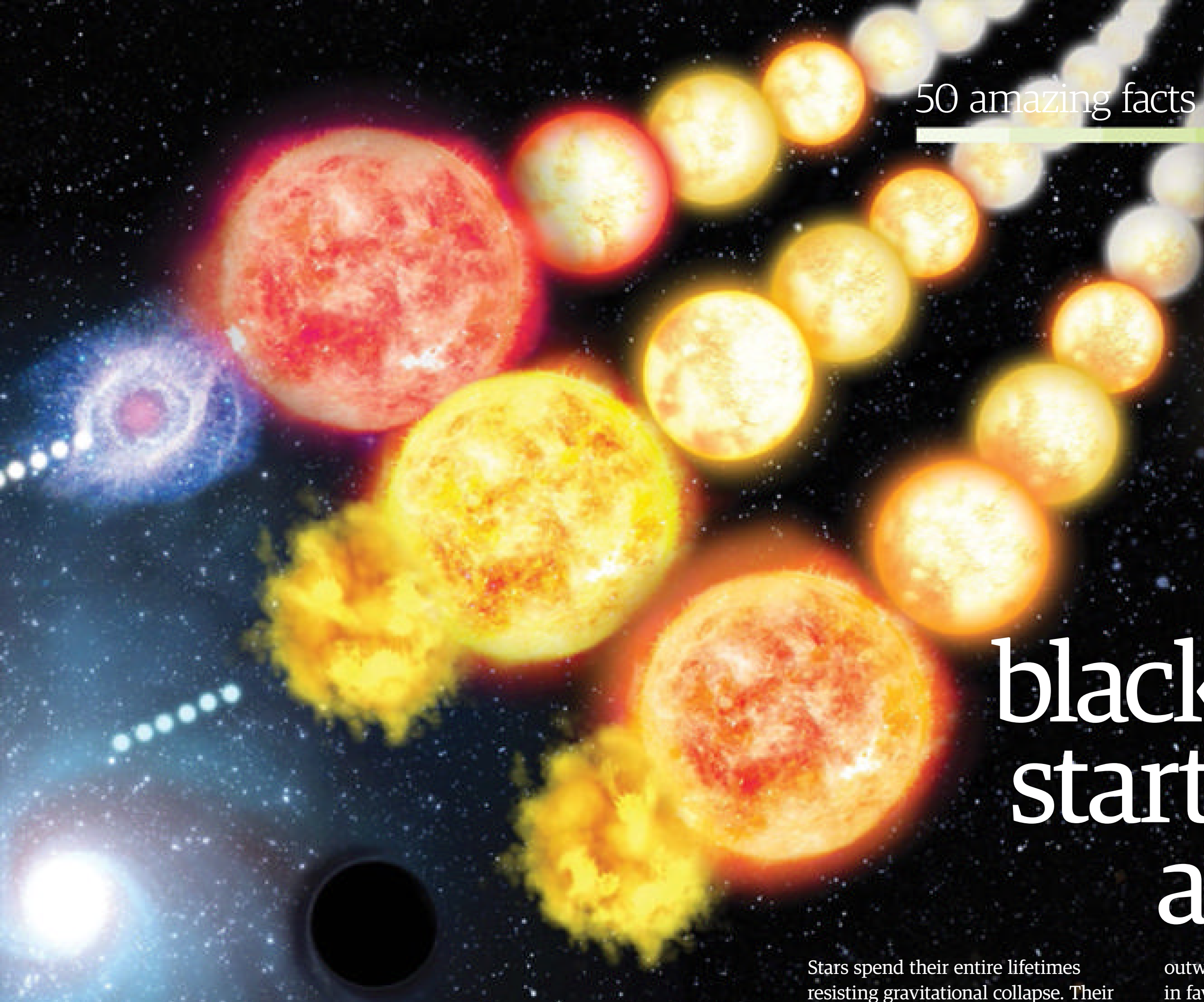


Dr Kathy Romer standing next to the Blanco Telescope, holding the DECam (top), and analysing its results



50 AMAZING FACTS ABOUT BLACK HOLES

Few things are as universally awe-inspiring and terrifying as black holes. These invisible behemoths are the great architects and the great destroyers of the universe



1 Many black holes started life as stars

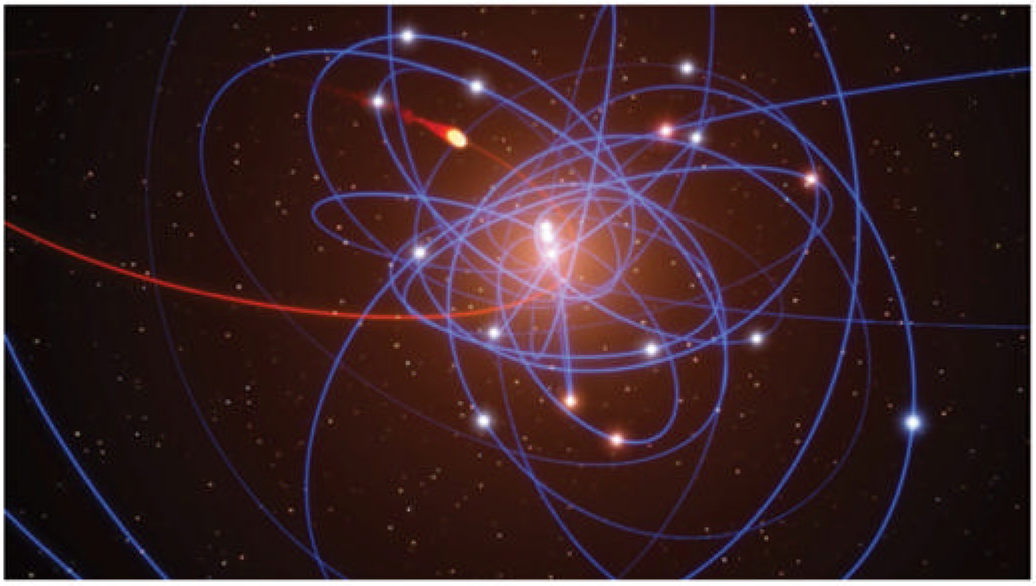
Stars spend their entire lifetimes resisting gravitational collapse. Their enormous mass means that the gas is continually pulled towards the core, but instead of collapsing down, atoms collide and fuse, releasing explosive atomic energy. Radiation pushes outwards against gravity, holding the star open as a glowing ball of gas.

As stars age, more and more of the atoms are fused, creating heavier and heavier elements, and eventually the fuel starts to run out. Without the outwards push, the balance is tipped in favour of gravity, and the star begins to collapse. For small stars, such as the Sun, the collapse is incomplete, and repelling forces manage to hold the last glowing embers open as a white dwarf star. For a white dwarf star that is larger than 1.4 times the mass of the Sun (known as the Chandrasekhar limit), these forces are insufficient, and the star continues to crunch inwards, forming a dense neutron star, or a black hole.

"As stars age, the fuel eventually starts to run out"

2 Supermassive black holes do not destroy everything around them

Actively feeding supermassive black holes are some of the most violent places in the universe, and quasars devour the equivalent of tens to thousands of Suns each year, but amazingly, the galaxies that surround them do not disappear into the abyss. Despite their frightening reputation, black holes do not actually behave very differently to other massive objects in the universe, unless you get too close. Just as the Earth will not spontaneously crash into the Sun, objects in stable orbits around black holes are in no danger of being swallowed.



3 Black holes slow the flow of time

To an outside observer, an object falling into a black hole appears to slow down, before stopping, caught in suspended animation at the boundary.

4 A black hole reveals no clues about what it has swallowed

As matter enters a black hole it is stretched, pulled and eventually shredded. Even if something were to leak out, it would bear no resemblance to what went in.

5 They have no size limit

In theory, black holes continue to grow in size indefinitely, but just how large they are able to get depends on their local environment.

6 Supermassive black holes are around the same mass as the Solar System

Supermassive black holes contain the mass of at least 100,000 Suns compressed into a space that is around the size of our Solar System.

7 It's the size of a black hole that matters, not its mass

Just a few micrograms of matter would be enough to create a black hole if it was compressed into a small enough space.

8 Some galaxies might harbour ultramassive black holes

The galaxy OJ 287 has two black holes, one of which is thought to contain the mass of around 18 billion Suns.

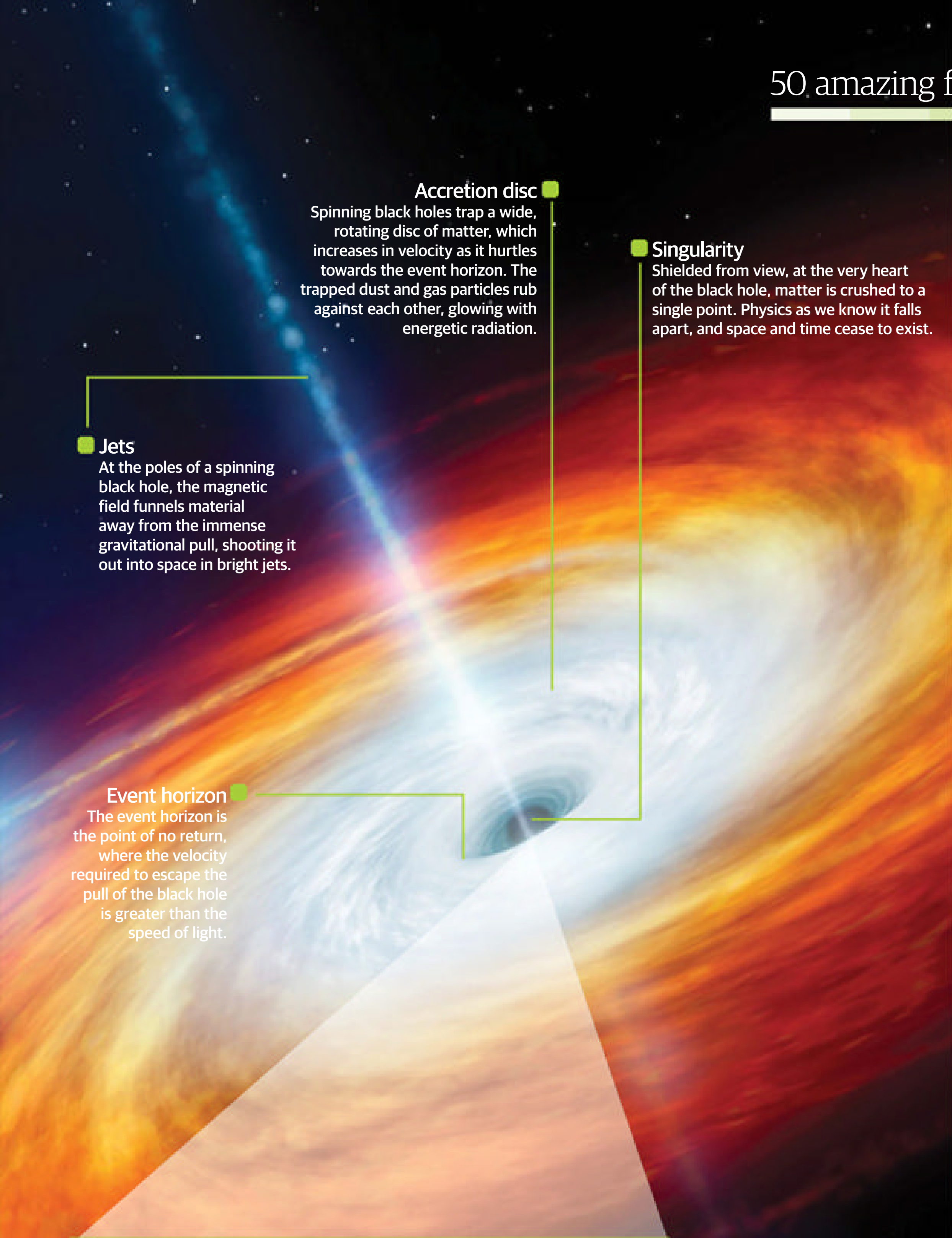
9 Black holes feed on stars, revealing their location

Black holes cannot be seen directly, but the effect they have on their surroundings often reveals their presence. In the Cygnus constellation, a blue supergiant star is being pulled into a teardrop shape, causing its light to flicker as it spins. The star orbits once every 5.6 days, and as it turns, the outer layer of gas is stripped away from its surface at 1,500 kilometres (932 miles) per second as it is funnelled towards an invisible point.

The supergiant is part of a binary system, and is locked in a fatal dance with a black hole, known as Cygnus X-1. As the black hole spins, space and time spiral up with it, and dust and gas from the star accumulate in a vast swirling whirlpool known as the accretion disc. Particles spiral towards the event horizon, like water circling a drain, and as they tumble inwards the friction releases bright flashes and flares of X-ray light.

10 Black holes spin faster than the stars that made them

If a star is spinning when it dies, it will continue to spin if it becomes a black hole. However, it will not spin at the same speed. Imagine the star is a twirling ice skater, holding his arms outstretched. As he spins, he pulls his arms inwards, and starts to spin faster. This is down to the law of conservation of angular momentum. As the matter collapses in towards the centre of a dying star, its diameter decreases and, like the ice skater, it spins faster.

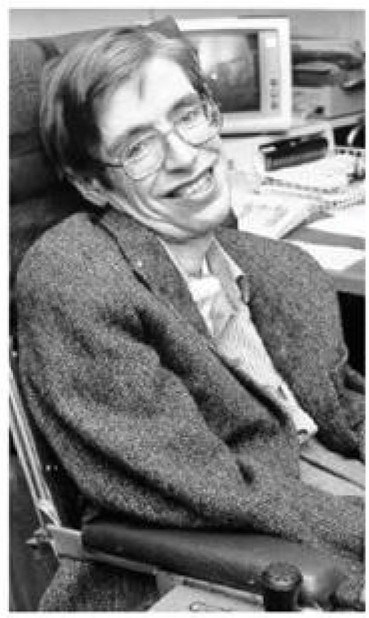


11 The centre of a black hole could contain a singularity

The event horizon of a black hole can measure thousands of kilometres in diameter, but once matter crosses over the edge it does not stop moving. Exactly what happens on the inside is debated, but according to Einstein's theory of general relativity, the curvature of space-time inside a black hole is extreme, and everything is directed towards a single point, known mathematically as a singularity. Every possible path leads back to the centre, and matter becomes so crushed, into such a tiny space, that it is unrecognisable. The singularity is infinitely small, and infinitely dense, creating an infinite curvature in space-time. Within a region of space known as the event horizon, anything that crosses over is compelled towards the centre with no hope of escape.

12 Some black holes have jets

Some black holes spew impressive amounts of energy from their poles, marking their location like a beacon. As dust and gas race towards the event horizon of a spinning black hole, magnetic field lines direct some of the energy outwards, funnelling it into two energetic jets, like a particle accelerator. NASA's Wide-field Infrared Survey Explorer (WISE) has identified a pair of black holes orbiting one another, which together create gravitational and magnetic disturbances so intense that their jets are being warped and twisted into ribbon-like spirals.



13 They slowly leak radiation

Stephen Hawking showed that black holes could actually radiate energy, known as Hawking radiation, releasing their scrambled contents back into the universe.

14 It takes millions of years to orbit our supermassive black hole

Sagittarius A* lies around 26,000 light years from the Solar System, and it takes 225 million years for us to complete a single orbit around the galactic centre.

15 They were originally known as dark stars

The idea of black holes has been around much longer than the science that predicts their existence, but in the 18th Century they were known as 'dark stars'.

16 Cygnus X-1 was the first black hole to be identified

Cygnus X-1 is one of the brightest radio sources in the sky, and is currently in the process of devouring a blue supergiant.

17 Black holes create waves

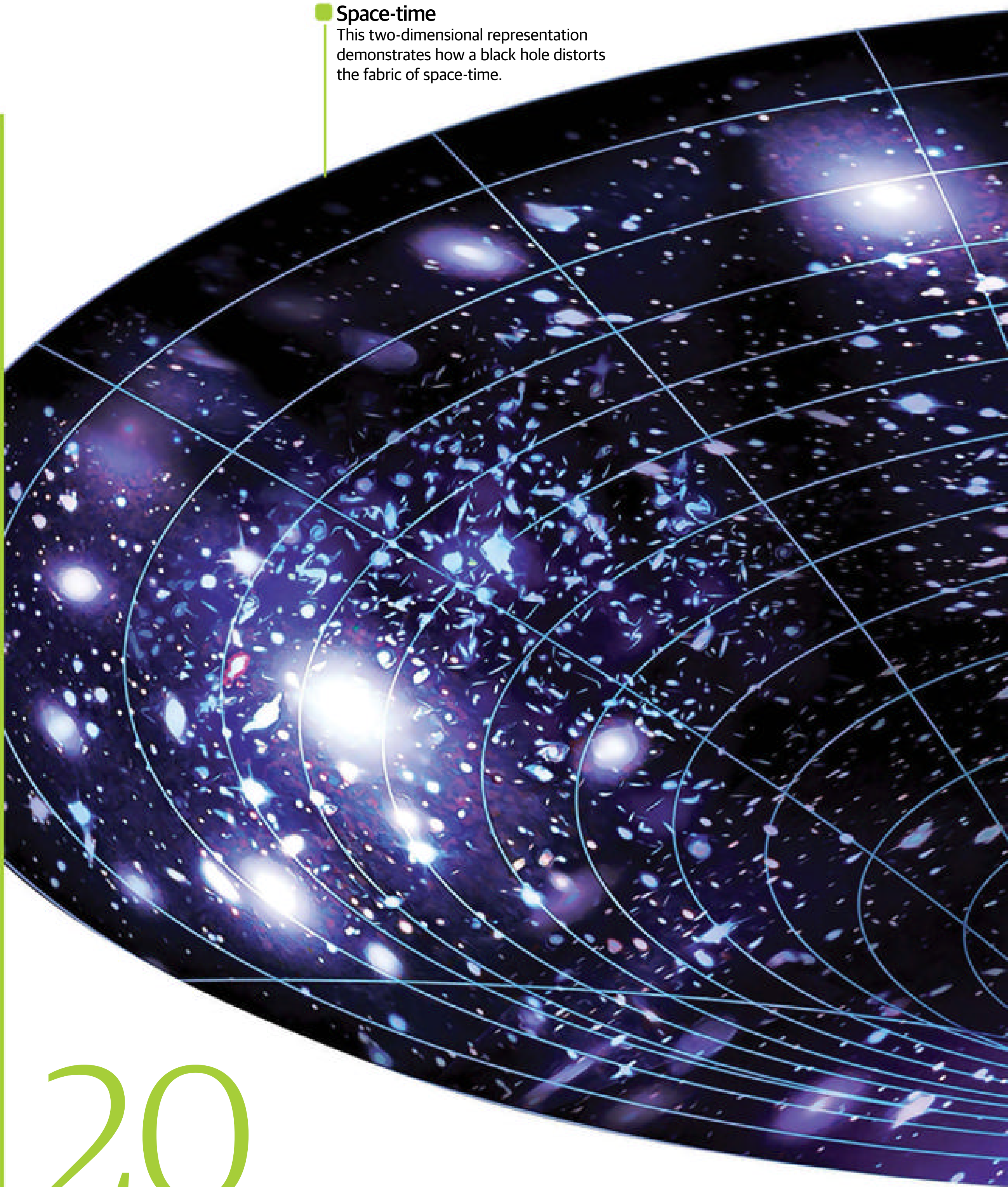
Albert Einstein predicted that as massive objects, like black holes, move through space, they create gravitational waves that ripple through space-time.

18 The universe is shaped by black holes

Supermassive black holes are found at the heart of almost all large galaxies, and act as the linchpins of the universe, around which stars and planets turn.

19 Stellar black holes contain the mass of five or more Suns

Black holes formed during the death of a star usually contain at least as much mass as five Sun-sized stars, compressed into an area measuring just a few kilometres across.



Space-time
This two-dimensional representation demonstrates how a black hole distorts the fabric of space-time.

20 Black holes bend space-time

Albert Einstein showed that the universe is made from a fabric, known as space-time, and, just like a piece of cloth, it can be bent, twisted and stretched. Massive objects, including planets and stars, make dips in the fabric of space-time, like bowling balls sitting on top of a trampoline.

The more mass that is collected in one area, the more of an impression it makes in the fabric, and the more energy is required to escape its gravitational field.

One object in orbit around another can be thought of as being similar to a cyclist in a velodrome. The cyclist is trying to travel in a straight line, however, the curved floor forces them to move around in circles. If they pedal faster, they might be able to get up enough speed to climb out of the top of the dome, and if they slow down, they will start to drift back in towards the centre.

21 Black holes are spherical

Black holes are often depicted as being funnel-shaped, but these two-dimensional diagrams are simply used to explain the idea that massive objects cause space-time to bend. In reality, space has at least three dimensions, and the impression that a black hole makes in space-time is much more complicated. The black hole itself, like most massive objects, is actually spherical. Gravity acts equally in all different directions around it, and the event horizon represents the point beyond which gravity becomes so intense that it is inescapable. It is the same distance from the centre of the black hole, no matter which direction you approach it from.

Interview

We spoke to head of the Nuker Team, Prof Douglas Richstone, about the origin of supermassive black holes

22 Almost every good-sized galaxy has a supermassive black hole

For every galaxy that is reasonably good sized and regular (that is, a galaxy with a disc and a bulge, and possibly spiral arms, or a so-called elliptical galaxy that looks round) there is a black hole. Moreover, the black hole's mass tracks the mass of the host galaxy (and is about 1/1,000 of the galaxy's mass). These black holes range from 1 million to nearly 10 billion solar masses.

However, for galaxies that are very small, or irregular, or possibly only have a disc and no round component (bulge), the situation is much more complicated. Some of these galaxies appear to have black holes and others don't.

23 Quiet supermassive black holes used to be quasars

We don't know for certain how the big black holes noted above form, but there is a clue. The amount of mass in galaxies at present tied up in black holes is almost exactly the amount of mass needed to power quasars (very bright objects thought to be black holes accreting matter) when the universe was about a fifth of its present age. So it is reasonable to identify the black holes in galaxies now as the relics of quasars.

24 It's impossible to see them directly

Black holes do not emit or reflect electromagnetic radiation (except Hawking radiation), but their gravitational effects are detectable.

25 Some black holes spin at half the speed of light

By looking at the pattern of X-rays in the area surrounding a black hole, the speed at which it is spinning can be determined.

26 There are two types of black hole

Schwarzschild black holes are the simplest, and are made up of just an event horizon and a singularity. Kerr black holes rotate, and have a third component known as the ergosphere.

27 Black holes are noisy

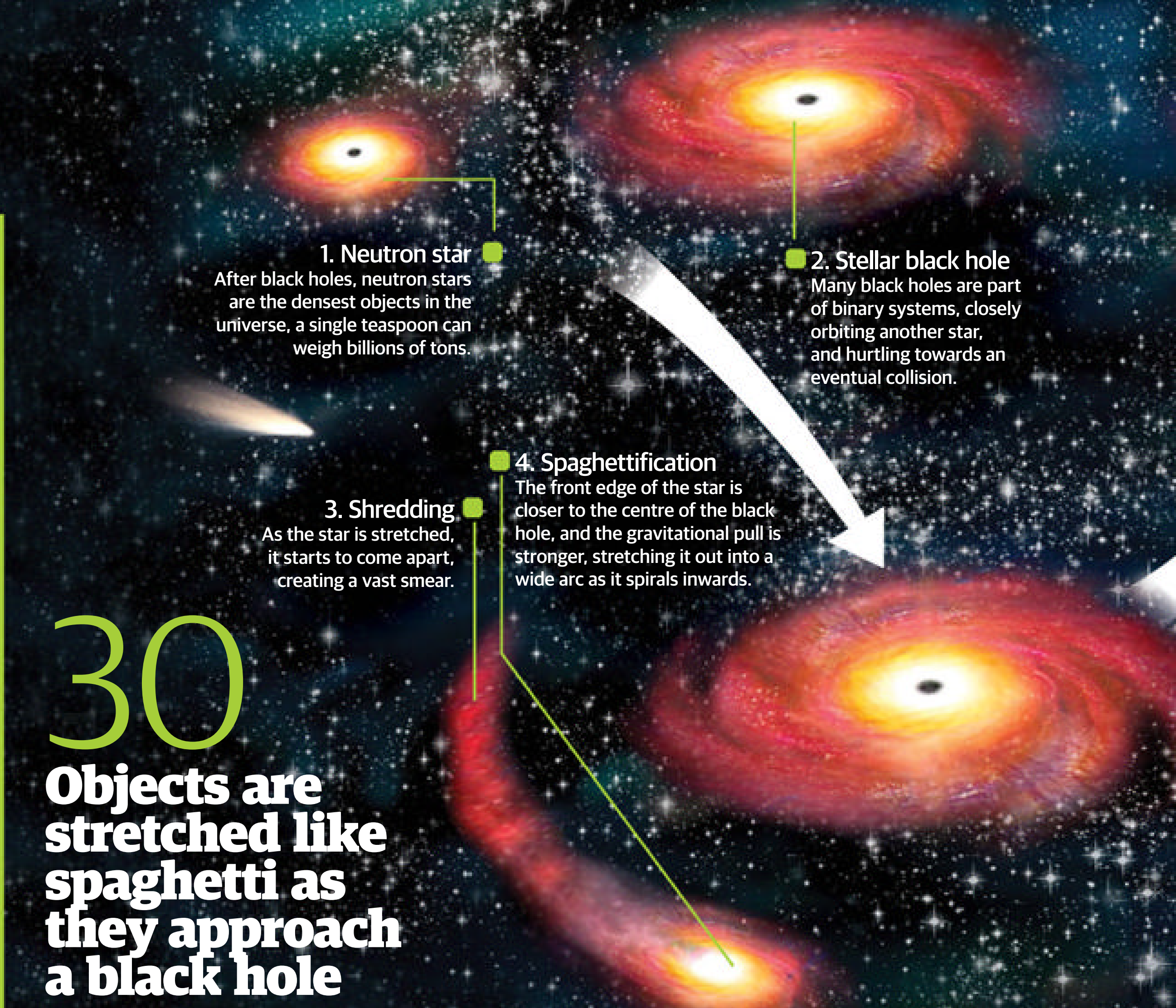
In 2003, NASA's Chandra X-ray observatory revealed that a black hole in the Perseus cluster makes a sound in the pitch of B flat.

28 We'll never know what is really inside a black hole

Light cannot escape across the event horizon of a black hole, preventing us from seeing in; there is no definitive answer about what really happens inside a black hole.

29 One day, black holes will dominate the universe

Black holes evaporate so slowly that they will exist long after the last of the stars fade and die, leading scientists to predict that one day they will be all that is left in the universe.



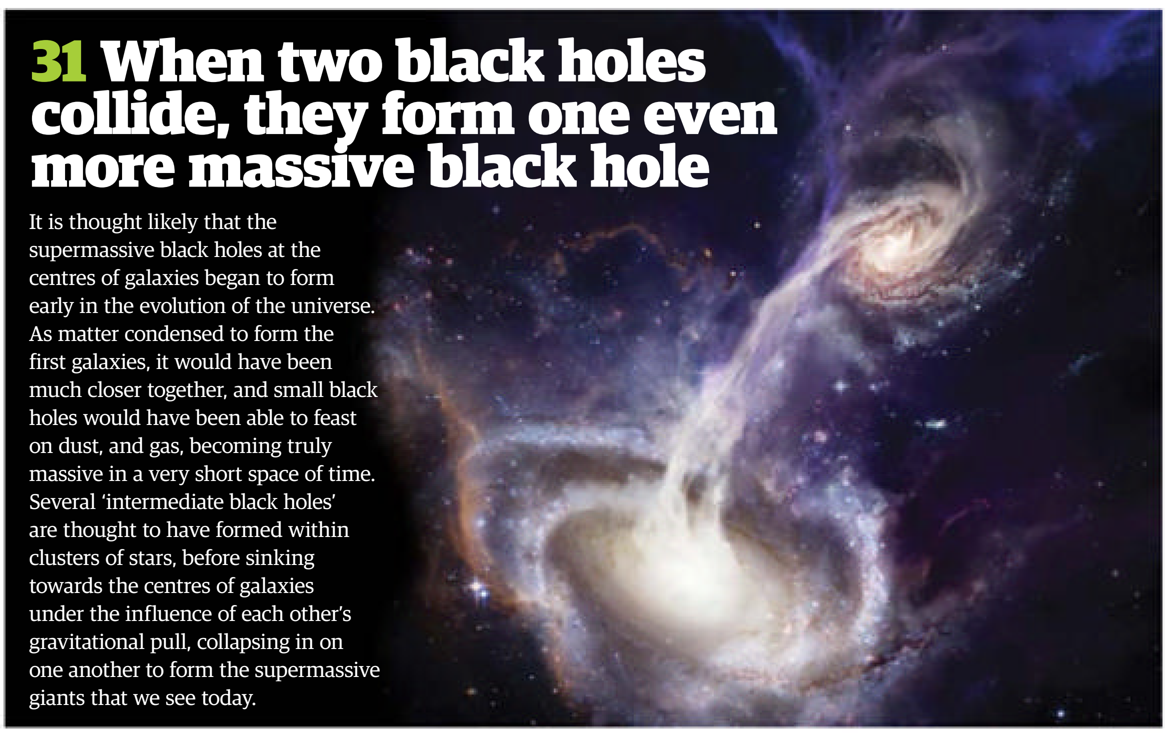
30 Objects are stretched like spaghetti as they approach a black hole

As an object gets closer to a black hole, the gravitational pull rises sharply. The parts of the object that are closest to the black hole experience stronger attraction than those farther away, causing them to accelerate faster. This stretches the object as the front moves more quickly than the back, drawing it out into a long filament in a process known as spaghettification.

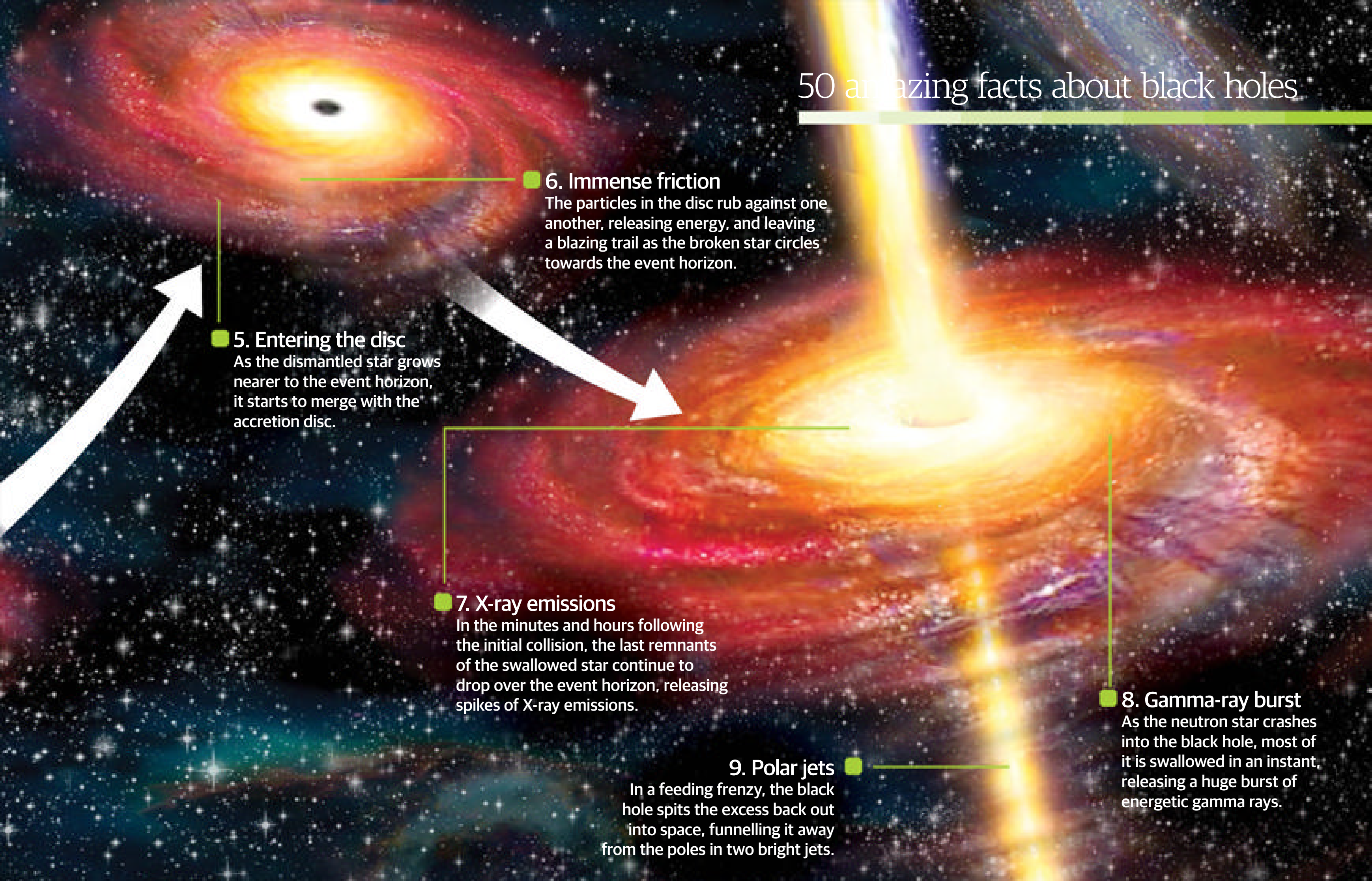
The tidal forces around a black hole are strong enough that anything entering becomes stretched, from the largest stars, to the smallest atoms. When the stretching force exceeds the elastic limit of the material it starts to break apart, continuing to tear into smaller and smaller pieces, each being stretched out like spaghetti, until all that is left are the elementary particles.

Spaghettification takes place at different times depending on the

31 When two black holes collide, they form one even more massive black hole



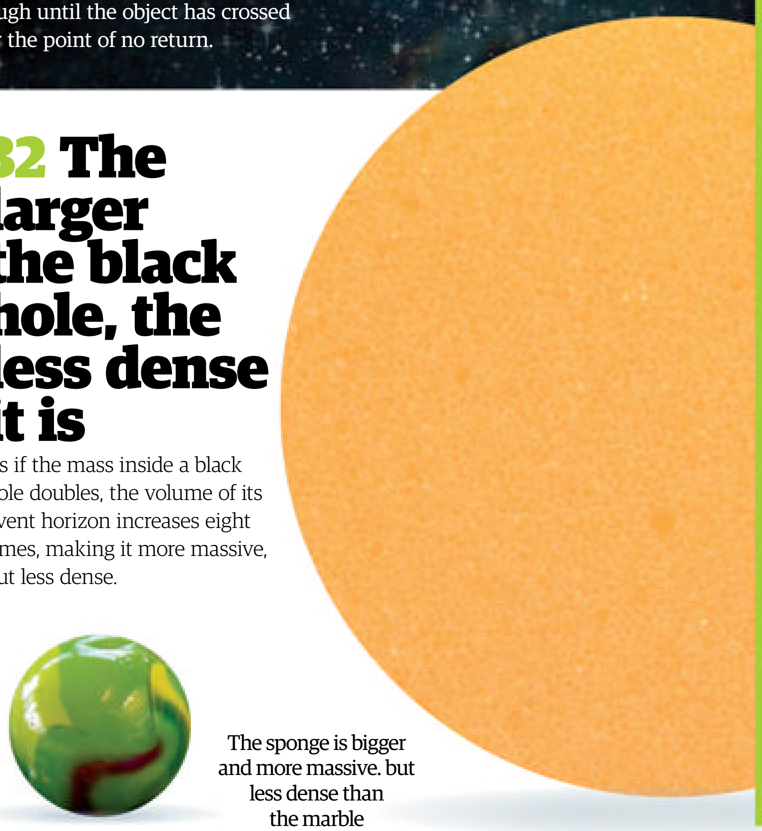
It is thought likely that the supermassive black holes at the centres of galaxies began to form early in the evolution of the universe. As matter condensed to form the first galaxies, it would have been much closer together, and small black holes would have been able to feast on dust, and gas, becoming truly massive in a very short space of time. Several 'intermediate black holes' are thought to have formed within clusters of stars, before sinking towards the centres of galaxies under the influence of each other's gravitational pull, collapsing in on one another to form the supermassive giants that we see today.



size and type of black hole. For small, stellar black holes, for example, it occurs before objects have crossed the event horizon. However, in supermassive black holes, the tidal forces do not always become great enough until the object has crossed over the point of no return.

32 The larger the black hole, the less dense it is

As if the mass inside a black hole doubles, the volume of its event horizon increases eight times, making it more massive, but less dense.



The sponge is bigger and more massive. but less dense than the marble

Interview

33 Even dwarf galaxies can harbour supermassive black holes

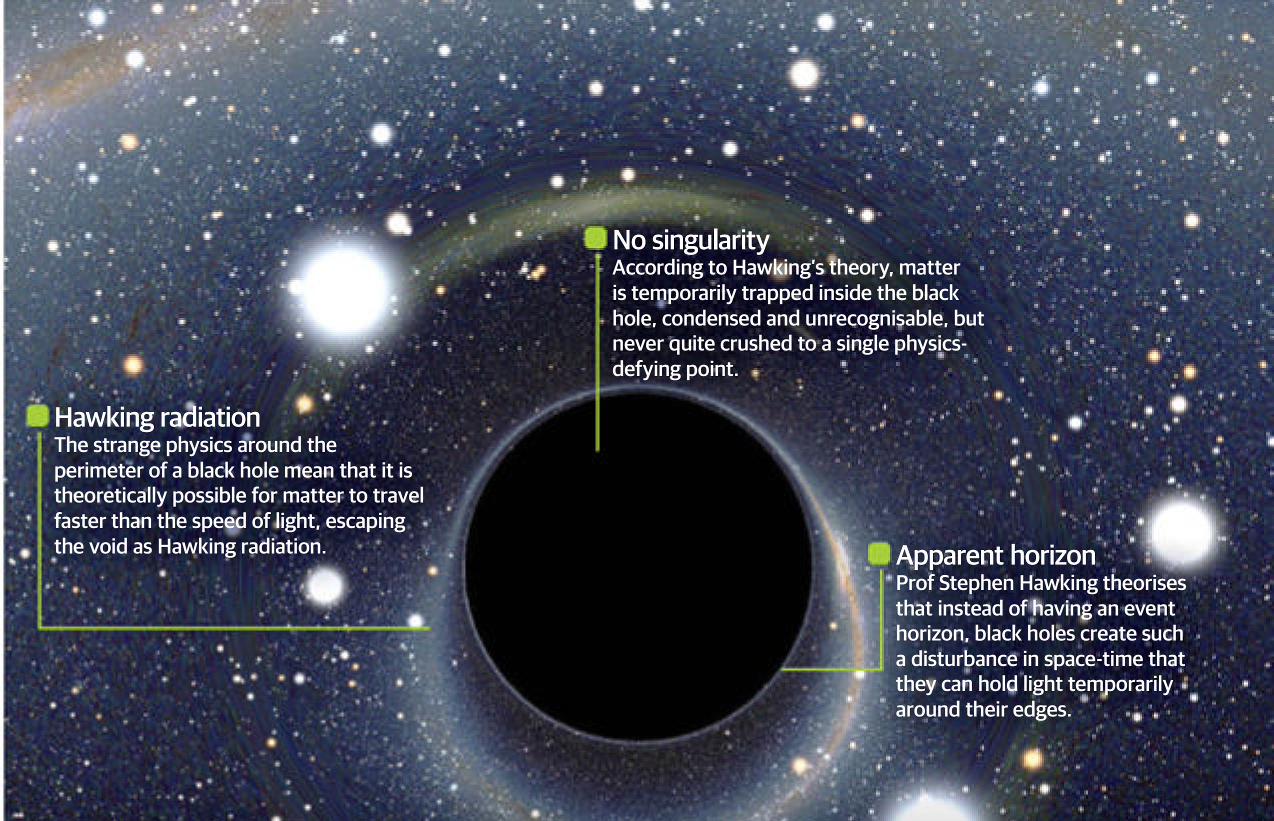
Prof Anil Seth, University of Utah, recently discovered a supermassive black hole at the centre of a dwarf galaxy

What makes the supermassive black hole in the dwarf galaxy M60-UCD1 such an interesting find?
We think most big galaxies have supermassive black holes, but M60-UCD1 is much smaller and less massive than any other galaxy with a supermassive black hole. Supermassive black holes play an important role in how galaxies form, and this provides a new environment for us to find these objects. Currently we don't understand how they form because their formation happened so early in the universe.

How did such a big black hole form in such a small galaxy?
M60-UCD1 got its name because it is just 22,000 light years from the giant elliptical galaxy M60 (this is closer than we are to the centre of our galaxy). We think that M60-UCD1 is in orbit around M60 and was once a much larger galaxy. When it passed close to the centre of M60, this bigger galaxy had its outer parts stripped away leaving just the dense core of stars and the black hole behind.

34 Black holes were first imagined in the 18th Century

Scientists John Michell and Pierre-Simon LaPlace were the first to wonder about the existence of black holes, imagining that beyond a certain point, the gravity of a massive object must become so great that nothing can get away. The trouble was, according to Isaac Newton's theory of gravitation, light wouldn't be affected by gravity, because it has no mass. So, no matter how massive an object became, light should be able to escape. It wasn't until Einstein's theory of general relativity that the physics of black holes really started to make sense.



35 Black holes might not exist

In 2014, Stephen Hawking put forward a controversial theory about black holes; that they do not exist at all, at least not in the way we imagine them. The science of black holes is based on Einstein's theory of general relativity, but there are grey areas that don't quite make sense. One of the major problems is the event horizon.

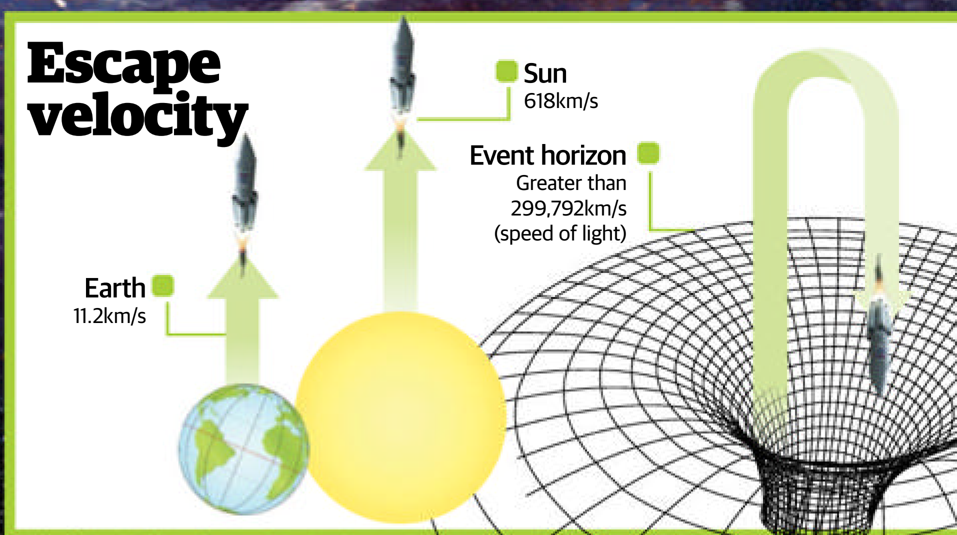
According to Einstein, the point at which matter crosses over into a black hole and gets destroyed as it's spaghettified and pulled towards the singularity. However, according to quantum theory, the event horizon would actually be a 'firewall' of high-energy particles. The physics behind Einstein's theory contradicts that of quantum theory, but Hawking proposes a new answer; that the event horizon does not actually exist at all. He suggests that black holes are not bottomless pits from which nothing can return, and that instead, they just temporarily hold and scramble matter, before releasing it back into the universe as radiation.

36 Black holes regulate their own size

Feeding generates intense radiation, which pushes outwards, clearing an enormous hole near the black hole, and limiting its growth.

37 Even a rocket travelling at the speed of light could not escape from a black hole

As objects become more massive and more dense, it becomes increasingly hard to escape their gravitational pull. For a rocket to escape the gravity of the Earth, it must travel at a speed of 11.2 kilometres (seven miles) per second, from the surface of the Sun, that speed rises to 618 kilometres (1,005 miles) per second, and from a dense white dwarf star, like Sirius B, the same rocket would need to travel at 5,200 kilometres (3,231 miles) per second in order to escape. Within the grip of a black hole, even a rocket travelling at the breakneck speed of light, 299,792 kilometres (186,282 miles) per second, would be unable to free itself from the immense gravitational pull.



38 Some can be very tiny

The smallest theoretical mass for a black hole is around 22 micrograms, a value known as the Planck mass.

39 The closest black hole is 6,070 light years away from Earth

The closest black hole to Earth is Cygnus X-1, and is located on the Orion Spur of the Milky Way and has the mass of about 15 Suns.

40 "Black holes have no hair"

This famous statement made by scientist John Wheeler describes the simplicity of black holes. Typically, they can be described by just three quantities: their mass, angular momentum and electric charge.

41 They halt local star formation

The largest and most active supermassive black holes often occur in the quietest galaxies. The radiation released as they feed stops the gas around them condensing to form stars.

42 The Sun could never become a black hole

To become a black hole, a star must be so massive that it completely collapses under its own gravitational pull. The Sun is much too small, and instead, it will end its life as a white dwarf.

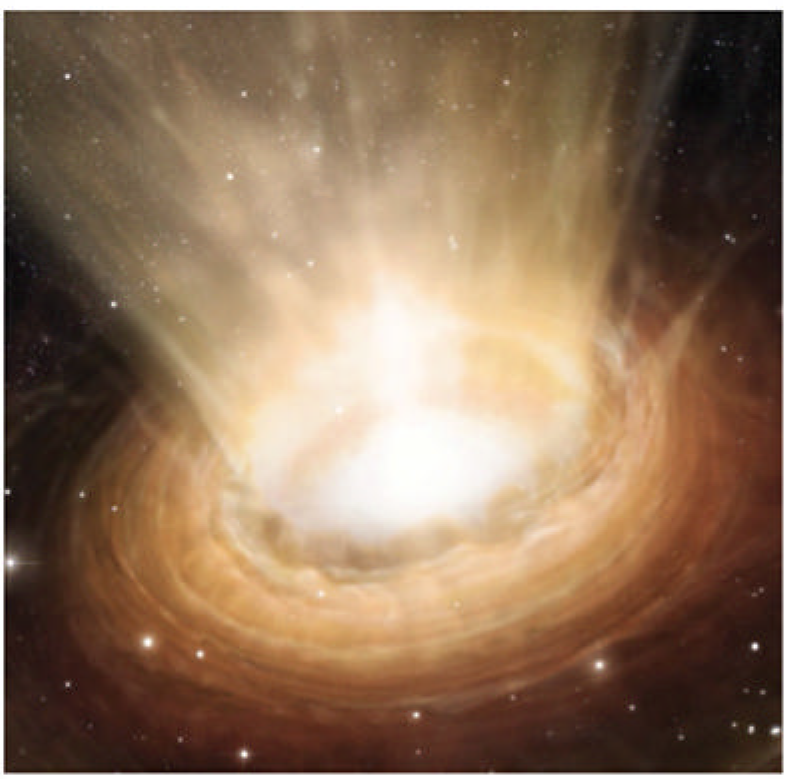
43 Black holes come in different sizes

Stellar-mass black holes can measure just a few kilometres in diameter, whereas supermassive black holes can be the size of our Solar System.

44 There is a supermassive black hole at the centre of the Milky Way

At the centre of the Milky Way, the stars move in strange circles. They hurtle towards a bright radio source, turn in a tight hairpin, and then race away again. Tracing the lines of their orbits reveals that they all overlap at a single point, known as Sagittarius A*.

The region is shrouded in a thick cloud of dust and gas, making it difficult to see, but in order to account for these highly elliptical orbits, astronomers have calculated that Sagittarius A* must contain around 4 million solar masses, compressed into a volume with a radius of about 25 million kilometres (15.5 million miles). In other words, it is a supermassive black hole.



45 Some black holes power the brightest objects in the universe

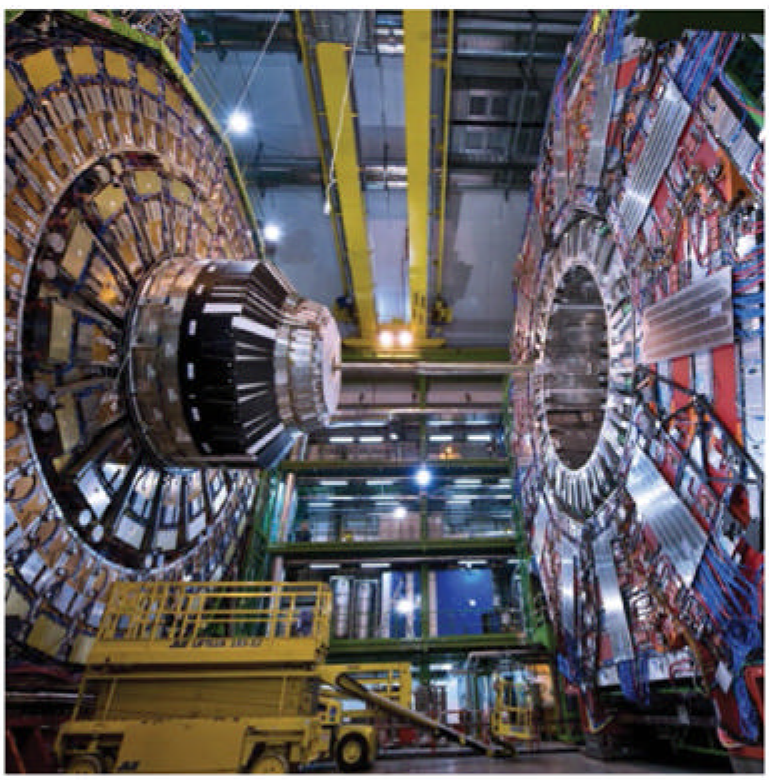
In the Sixties, US astronomer Allan Sandage noticed a very bright object in the distant sky. From Earth, it was as bright as a nearby star, but its vast distance meant that it must be emitting hundreds of times as much energy as all of the stars in the Milky Way combined. Dubbed quasars, these objects are among the brightest in the universe, and represent actively feeding supermassive black holes. Thousands have been identified, and each blazes brightly as matter tumbles on to its accretion disc, spewing X-rays and visible light into space, and producing energetic jets from its poles.

Strange things happen around supermassive black hole Sagittarius A*

46 Particle accelerators could create micro black holes

When the Large Hadron Collider at CERN was switched on in 2008, there were concerns among scientists that the particles, travelling at close to the speed of light, could theoretically produce miniature black holes. So far, no such holes have been created, but it is definitely possible in theory.

Even if a micro black hole was created, there would be little to worry about. The black hole would be so incredibly small that it would take billions of years for it to consume just a single gram of matter, and if Stephen Hawking is correct, and black holes do leak radiation, the tiny black hole would decay long before this would ever happen.



47 Space around a spinning black hole is warped

Spinning black holes distort space-time, wrapping it into a swirl known as the ergosphere. Within this area, space itself moves faster than the speed of light.

48 W49B is the youngest known black hole in the Milky Way

An asymmetrical supernova remnant is all that remains of a star that exploded just 1,000 years ago. There is no evidence of a neutron star at its core, leading astronomers to believe that it harbours a young black hole.

49 Spinning black holes have a donut-shaped magnetic field formation

As matter swirls around the accretion disc of a black hole, the magnetic fields line up, forming a donut-shaped ring with the event horizon nestled in the hole at the centre.

50 Small galaxies contain medium-sized black holes

It was thought that black holes came in two sizes, stellar-mass black holes and supermassive black holes, but researchers using data from NASA's Chandra X-Ray Observatory and Rossi X-Ray Timing Explorer (RXTE) telescopes measured a medium black hole in Messier 82 to be around 400 solar masses. These 'intermediate-mass black holes' contain between 100 and 10,000 times the mass of the Sun.

Cosmic forces

Learn about the four forces that control our universe, from the movement of galaxies to formation of elements in a supernova

The four fundamental forces in space underlie every type of natural behaviour so far discovered and described by laws of physics. They vary hugely in terms of strength, range of operation, and the type of objects that they affect. Two of these forces are familiar to us from everyday life - gravitation, which attracts objects with mass to each other, and electromagnetism, which influences the movement of objects with electric charges. The other two, called the strong and weak interactions, have a less obvious influence on us - they are responsible for holding together the protons and neutrons in atomic nuclei, and for occasionally allowing them to disintegrate in radioactive decay events.

Gravitation was the first of these forces to be discovered, but it's still the most mysterious since it seems to operate in a very different way from the other three. It influences all objects with mass, and is responsible for everything from the fall of an apple or the orbit of a planet, to the extreme conditions around a black hole. Compared to the other fundamental forces it's actually very weak, only making its presence felt when matter is present in large amounts, but it operates over very long ranges. Moreover, while other forces work by the exchange of signal particles called 'gauge bosons', Einstein showed that gravity exerts its influence by distorting space and time themselves. So the paths of objects moving through a gravitational field, even massless photons of light, are deflected from straight lines.

Electromagnetism is also familiar. It explains the interlinked electrical and magnetic effects: electricity is simply the flow of charged particles, while magnetic forces act on electrically charged particles inside certain objects. In general, electromagnetism is stronger than the force of gravity but the range of its effects is less. In order to be influenced by electromagnetism at all, particles need to be imbued with either a positive or negative electric charge.

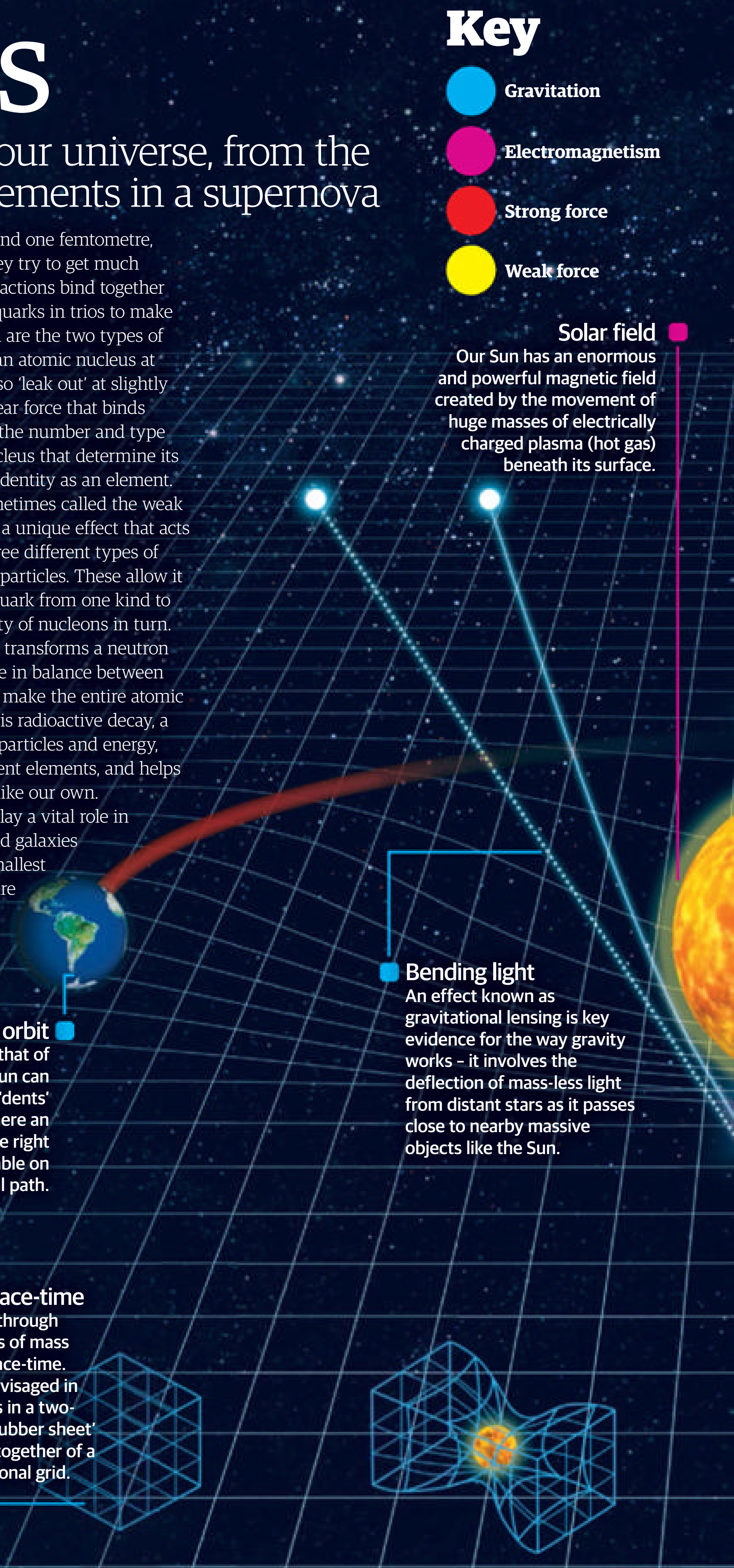
Light and other types of radiation such as infrared and X-rays, are electromagnetic waves generated by materials that are heated (like the surface of stars), or otherwise energised (like interstellar nebulae). Particle-like packages of waves, known as photons, are responsible for transmitting electromagnetic forces across space at the speed of light.

The two other forces only make their influence felt at unimaginably small scales, of around 1 million-billionth of a metre (a femtometre, or fm). Even at the relatively large scale of atoms, around one billionth of a metre, it's still the electromagnetic force that holds the negatively charged electron particles in orbit around the positively charged atomic nucleus.

The strong interaction acts on particles with a property called 'colour charge', though it has nothing to do with everyday colour. This is transmitted between them through the exchange of 'gauge bosons' called gluons. It is strongly attractive between particles at distances of around one femtometre, but repels particles when they try to get much closer than that. Strong interactions bind together elementary particles called quarks in trios to make protons and neutrons, which are the two types of 'nucleon' typically found in an atomic nucleus at the core of an atom. They also 'leak out' at slightly larger scales to create a nuclear force that binds these nucleons together. It's the number and type of nucleons in an atomic nucleus that determine its chemistry, and therefore its identity as an element.

The weak interaction (sometimes called the weak nuclear force), meanwhile, is a unique effect that acts over short scales and has three different types of force-carrying 'gauge boson' particles. These allow it to change the 'flavour' of a quark from one kind to another, changing the identity of nucleons in turn. The typical weak interaction transforms a neutron into a proton, and the change in balance between these two particle types can make the entire atomic nucleus unstable. The result is radioactive decay, a process that releases excess particles and energy, transforms atoms into different elements, and helps heat the interiors of planets like our own.

Therefore, all four forces play a vital role in forming the stars, planets and galaxies and their nature from the smallest particle upwards, but there are still many aspects of their behaviour that we need to understand further.

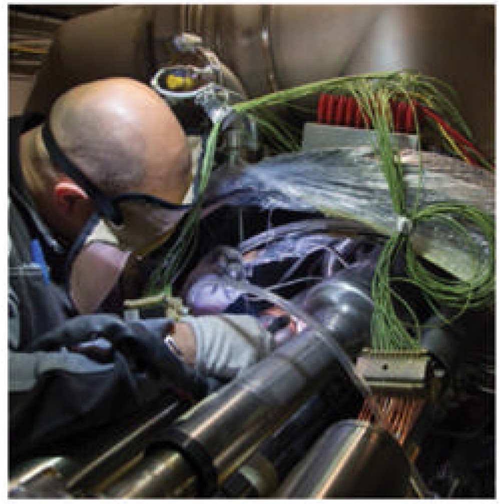


Fast fact

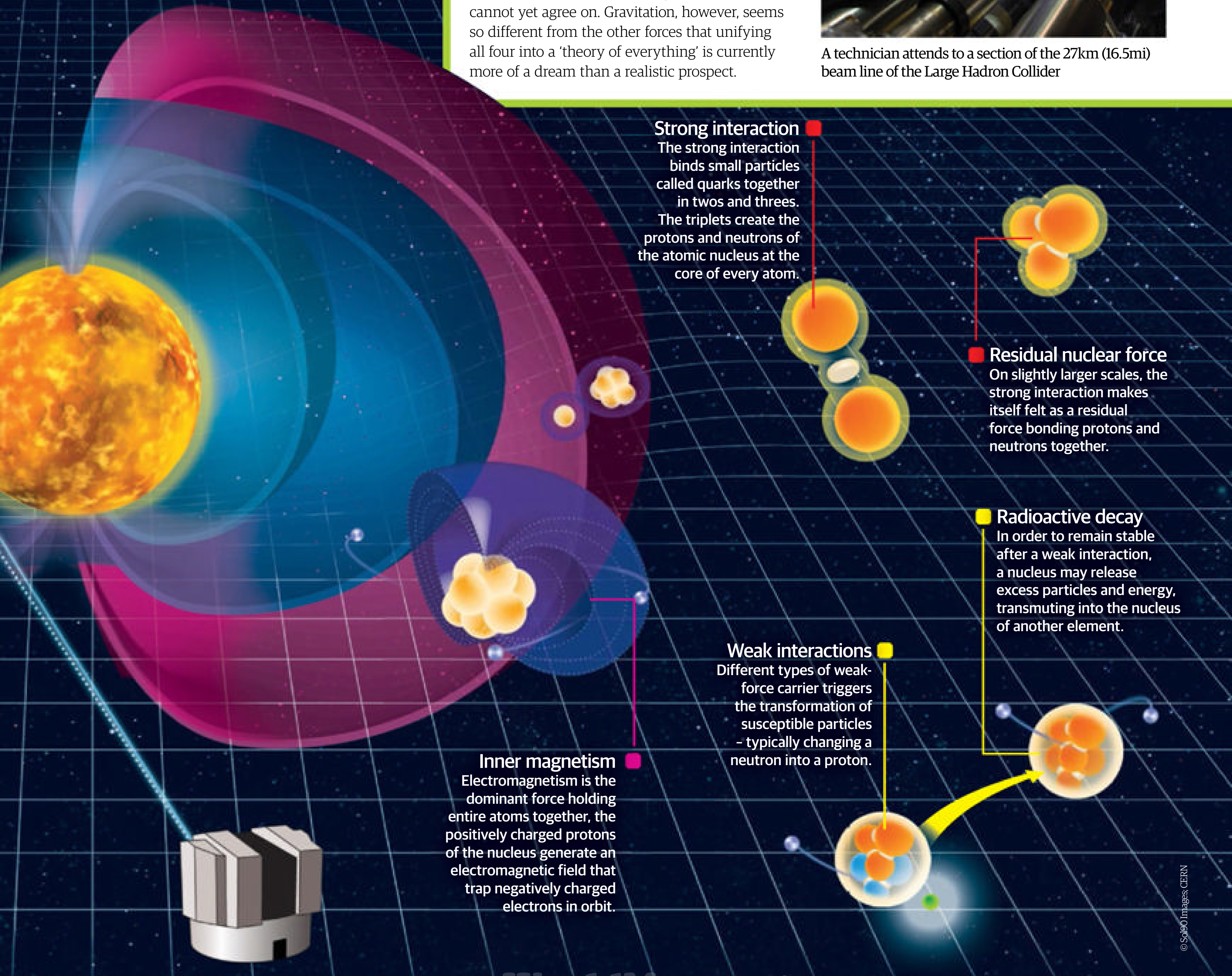
Some cosmologists think that gravitation's strange properties can be explained by much of its strength 'leaking out' into different dimensions, known as branes.

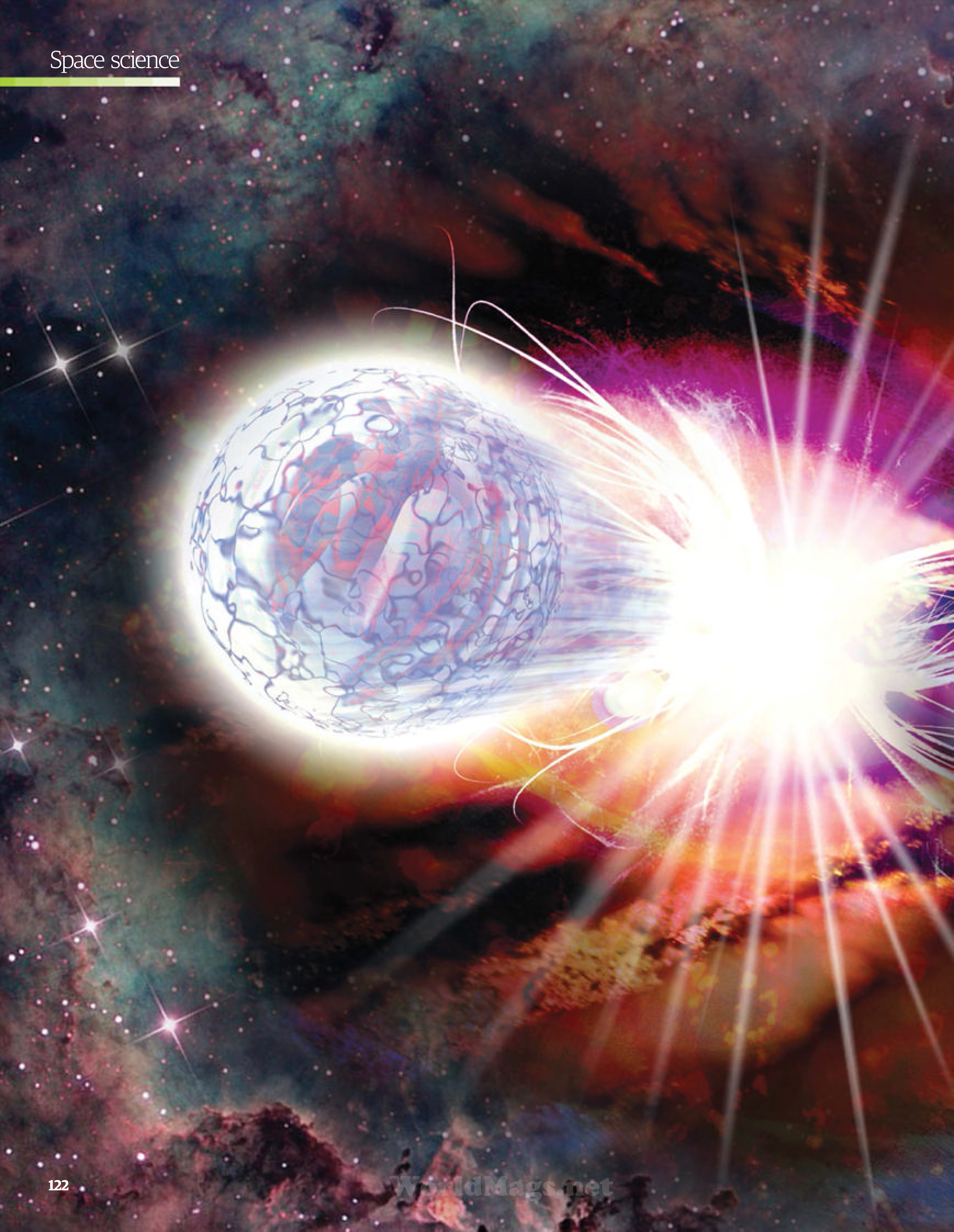
Unifying the forces

In their quest to understand the four fundamental forces of today's universe, physicists use both theory and experiment. Machines like the Large Hadron Collider slam particles into each other at tremendous speeds, briefly re-creating conditions last seen in the Big Bang. At these extremes, the electromagnetic force and weak interaction, for example, are unified in a single 'electroweak' force. Theorists believe that the four forces all emerged from a primordial superforce that split apart in the earliest moments of the universe after the Big Bang, and hope to ultimately combine the strong interaction with the electroweak force to model the 'electronuclear' force. This would be the elusive, so-called Grand Unified Theory that scientists cannot yet agree on. Gravitation, however, seems so different from the other forces that unifying all four into a 'theory of everything' is currently more of a dream than a realistic prospect.



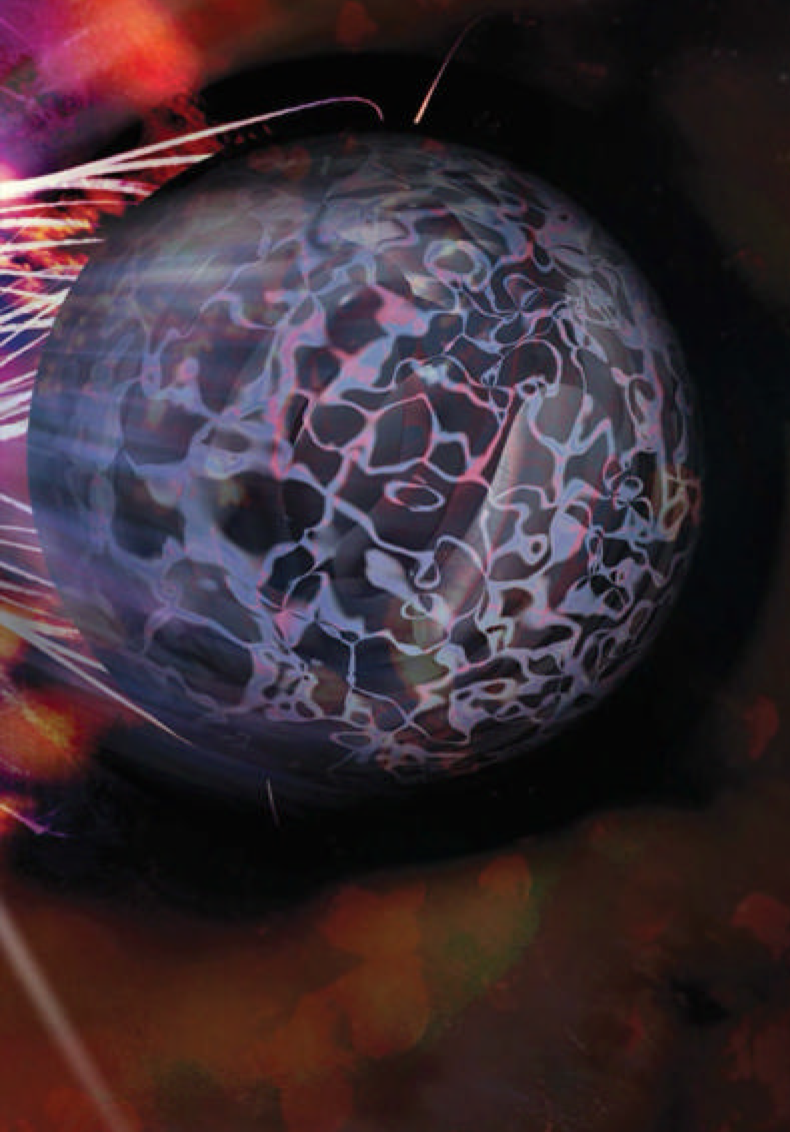
A technician attends to a section of the 27km (16.5mi) beam line of the Large Hadron Collider





THE POWER OF ANTIMATTER

Is antimatter the key to understanding more about our universe and propelling future spacecraft between the stars? We investigate how close we are to finding out more about this exotic and fascinating force



Imagine a mirror held up to the universe, one that reflects matter on the scale of particles. Just like a normal mirror, the image would be reversed. Particles like protons with positive charge would suddenly look to be negatively charged, while electrons that spin in quantum fashion one way would appear to spin the other way. While the universe doesn't really have a mirror, particles of matter do have mirror images of themselves, known as antimatter.

"[Matter and antimatter] are equal and opposite, that's the theory so far," says antimatter researcher and spokesperson for CERN's Antihydrogen Laser Physics Apparatus (ALPHA), Jeffrey Hangst. "The antiparticle equivalent - antiprotons, antineutrons and positrons - are just like their matter counterparts but they have an opposite charge in the case of the charged particles and when they meet they annihilate."

So when the two clash, they do so explosively. Just as Einstein's famous equation $E=mc^2$ describes the equivalence of mass and energy, when a particle and an antiparticle come into contact with each other, they utterly annihilate in a flash - there one moment, gone the next - converting all their mass directly into energy. It's for this reason that, if antimatter could be harnessed, we would have an impressive energy source on our hands. The trouble is, there's just not that much antimatter about.

That's the major problem with antimatter, especially when its far more common counterpart - common matter - is found lurking everywhere. Antimatter can be created then destroyed in such a short space of time that experts do not have much time to hold antimatter down long enough for us to question what about its existence makes it special. As a result, there are not only gaps in our knowledge when it comes to this shy matter itself, but also in our theories of how the cosmos came into existence. "The names matter and antimatter are a bit arbitrary," adds Hangst. "We believe that if you built a universe out of antimatter it would behave in the same way, so we don't know why nature chose one over the other."

Without a doubt, the Big Bang is a widely supported theory and it tells us that matter and antimatter should have been created equally at the beginning of time around 13.8 billion years ago. They should have annihilated each other leaving nothing behind, but we exist today in a universe with plentiful matter and scarcely a drop of antimatter. Thanks to our natural curiosity for exploring things and taking things apart to reveal the fundamental building blocks of matter, one thing remains unclear; what happened to the antimatter that once existed?

"[The study of antimatter] is motivated by the fact that we believe that matter and antimatter should have been produced in equal quantities at the [time of the] Big Bang and as far as we can observe so far the universe just contains matter, so we don't really know what happened," explains Hangst. "None of the theories that we have, or the so-called standard model [of particle physics] tell us what happened to the antimatter. That's one of the biggest

unsolved questions in physics – why is there a universe at all?"

While the Big Bang is an extraordinarily successful theory, as it currently stands, we shouldn't exist since the matter from which we are built from should have been annihilated away. The University of California's Professor Joel Fajans, who has recently enlisted the help of the ALPHA experiment to investigate if antimatter and matter are affected differently by gravity, echoes Hangst's and other scientists' thoughts that maybe there has been an error in our understanding of how much matter and antimatter was produced when the universe began. "I wish I knew why the amounts produced are not equal," he told us. "Understanding antimatter isincredibly important to our very existence."

And so, that's what experts have been trying to do ever since antimatter was first proposed by physicist Paul Dirac in 1931; study the ying to matter's yang in the hope of locking down something substantial, providing the answers to the mysteries of space that have eluded us for so long. A year after Dirac's proposition the first antiparticle – the positron – was discovered, followed by the antiproton and antineutron two decades later.

But in our attempts to delve into ways of pinning down antimatter, scientists have hit a few snags. Creating it artificially is one thing, but making enough of it and keeping it within our grasp for long enough is quite another. "First you have to produce [antimatter], it can't exist naturally [in significant quantities] in a matter universe so there are lots of very difficult technologies that you have to master to produce it and then to hold on to it," explains Hangst. "It needs to be held in a vacuum, a very, very good vacuum."

While the likes of Hangst and other scientists all over the world have been trying to get this down to a tee, Hangst insists that we still have much to figure out. "We are still learning how to efficiently produce it and handle it in a matter universe and even if you master these techniques, you are typically dealing with small quantities. It is not like you can buy a bottle of antihydrogen and make it [many] atoms at a time, so even after all that technology you are still left with very little of the substance."

CERN has been able to produce thousands of atoms of the simplest antiatom, antihydrogen, at a time, yet capturing it has proven to be problematic. "We've only managed to trap one atom at a time," explains Hangst. "We are really talking about a very, very rare substance." Nevertheless, ALPHA has been able to trap some antiatoms for as long as 1,000 seconds – holding them still long enough for scientists to study them before they annihilate.

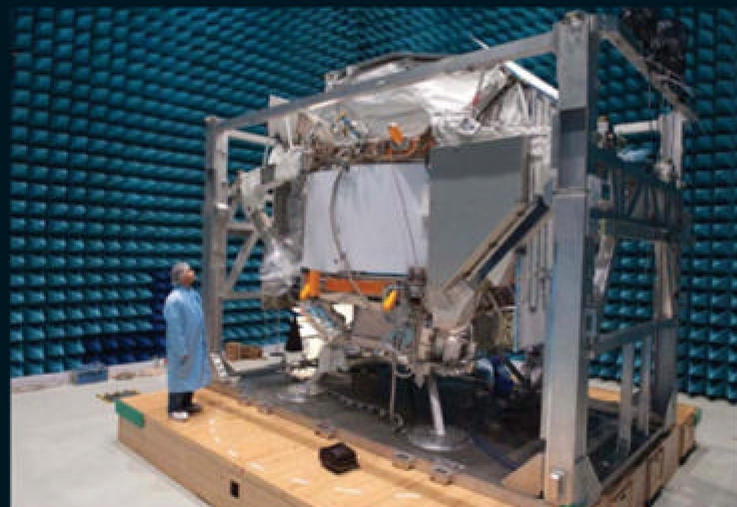
As a result of the painstaking methods used to make antiatoms, antimatter is deemed to be the most expensive material to produce with NASA suggesting that it would cost around $62.5 trillion (£41 trillion) to produce just one gram of antihydrogen. To date, only a few tens of nanograms have been created at particle accelerators like the Large Hadron Collider at CERN.

That's why as things stand antimatter is never going to be a power source of the future; there's just not enough of it to do anything with. "It takes more energy to make it than

> "We are still learning how to efficiently produce it and handle it in a matter universe"
> **Jeffrey Hangst, CERN**

Hunting antimatter

Mounted on the International Space Station, the Alpha Magnetic Spectrometer (AMS), or AMS-02, studies cosmic rays – beams of high-energy particles that permeate space – before they have a chance to interact with the Earth's atmosphere. Cosmic rays, which are believed to originate from beyond the confines of the Solar System, carry an excess of antimatter that has been detected by this sensitive particle physics experiment. This unusual excess in antimatter, or positrons, could help us to find evidence for the elusive dark matter – one of space's biggest mysteries – that is believed to account for a huge chunk of the universe's mass.



Here the AMS-02 is inside the Maxwell electromagnetic radiation chamber at the European Space Research and Technology Centre (ESTEC) for electromagnetic capability and interference testing prior to launch

Reaching a sensitivity that allows the instrument to test a greater volume of the universe than its predecessor for primordial antimatter, the AMS will study the composition of cosmic rays with a high accuracy for a decade from the ISS

A history of hunting for antimatter

1931

Existence of antimatter predicted
Theoretical physicist Paul Dirac pointed out that the Schrödinger wave equation for electrons, when considered in its relativistic form, suggested the existence of antielectrons.

1932

Scientists discover positron
During his investigation of cosmic rays, Carl Anderson from the California Institute of Technology came across unexpected particle tracks in his cloud chamber that seemed to have the same mass as the electron but an opposite, positive charge; the positron.

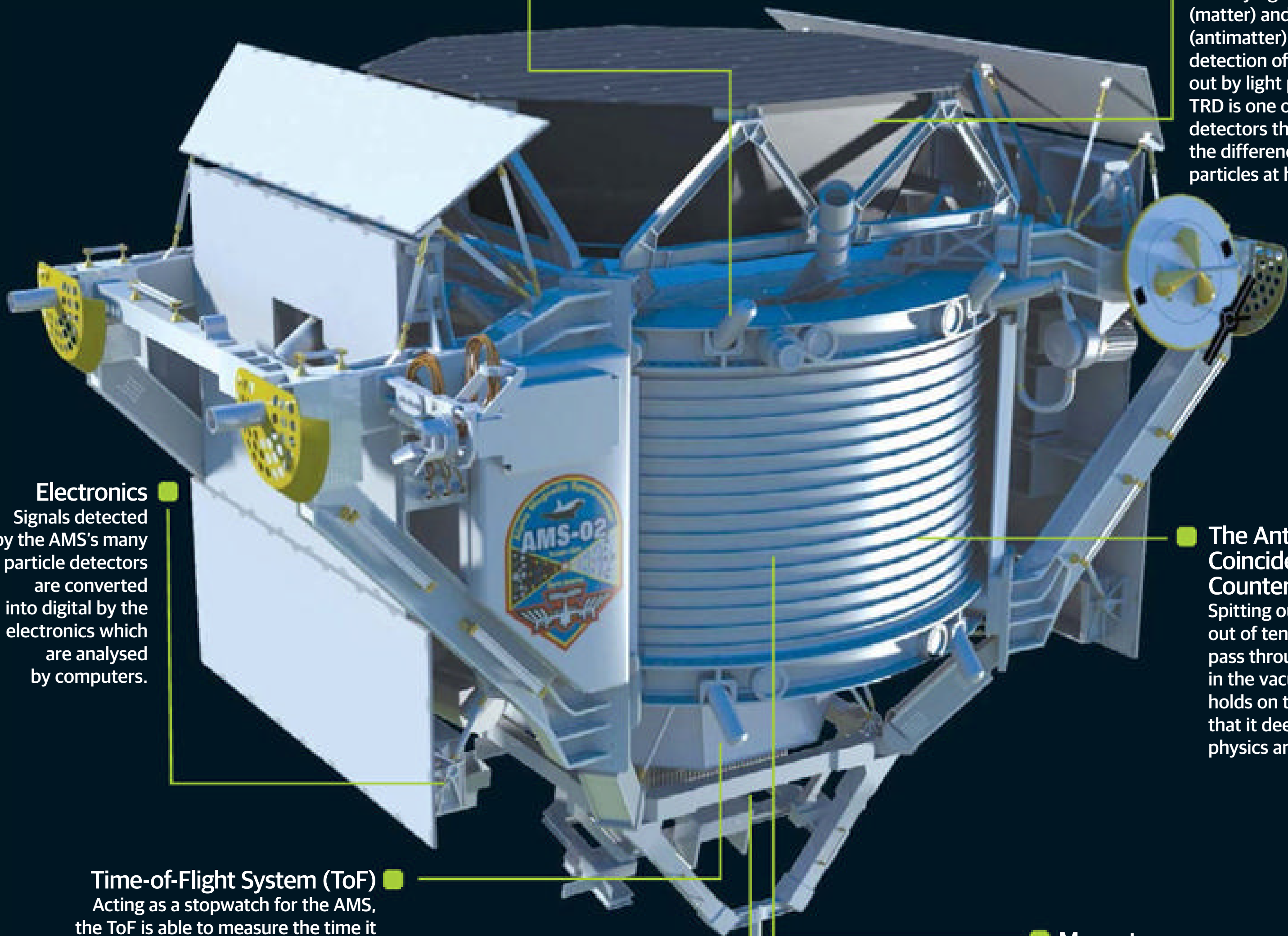
1955

The discovery of the antiproton
Confirmed at the University of California, Berkeley, Emilio Segrè and Owen Chamberlain were awarded the 1959 Nobel Prize in Physics for their discovery of the antiproton.

1956

Scientists discover the antineutron
Discovered at the Lawrence Berkeley National Laboratory, the antineutron was uncovered by physicist Bruce Cork in a proton-proton collision experiment.

Inside the AMS



Silicon Tracker
Hunting for matter and antimatter, this tracker is able to separate the two by determining the charge of the particle entering the AMS by measuring the deflection of the matter and antimatter.

Transition Radiation Detector (TRD)
Identifying electrons (matter) and positrons (antimatter) through the detection of X-rays thrown out by light particles, the TRD is one of the few detectors that can tell the difference between particles at high energies.

Electronics
Signals detected by the AMS's many particle detectors are converted into digital by the electronics which are analysed by computers.

The Anti-Coincidence Counter (ACC)
Spitting out a good eight out of ten particles that pass through it, the ACC, in the vacuum case, only holds on to particles that it deems useful for physics analysis.

Time-of-Flight System (ToF)
Acting as a stopwatch for the AMS, the ToF is able to measure the time it takes for a particle to pass through. The velocity of the particle can be measured up to an accuracy of 98% the speed of light. It also warns the sub-detectors of incoming cosmic rays.

Ring-Imaging CHerenkov Detector (RICH)
The velocity of a charged particle is determined from the Cherenkov effect – radiation which can travel faster than the speed of light in a particular material that produces a blue cone of light which is detected by RICH.

Magnet
At the heart of the AMS experiment rests the magnet which is able to separate matter from antimatter. It does this by bending the matter particles in an opposite direction to the antimatter particles thanks to their opposite charges.

1965
Antideuteron created in laboratory
The antiparticle of a nucleus of deuterium, antideuteron, was originally created at the Proton Synchrotron at CERN as well as at the Alternating Gradient Synchrotron at Brookhaven National Laboratory.

1995

CERN scientists observe antihydrogen
Antihydrogen was made artificially in accelerator experiments. However, the subsequent annihilation with matter meant that it could not be examined in detail.

2010
Atoms of antihydrogen trapped at CERN
The Antihydrogen Laser Physics Apparatus (ALPHA) team at CERN produced and managed to confine cold antihydrogen for about a sixth of a second, marking the technique that would see antihydrogen maintained for over 15 minutes.

2013
Scientists study antigravity for first time
Scientists uncovered the first direct evidence of how antimatter interacts with gravity. However, while it is undecided if antigravity truly exists, measuring antimatter gravity is proven to be possible.

Why is antimatter important?

1 To understand our existence "The Big Bang should have produced as much antimatter as matter and then it should have all mutually annihilated, leaving nothing," says Professor Joel Fajans. "Yet we are here, and we've observed almost no antimatter. It's the biggest outstanding problem in our understanding of the early universe."

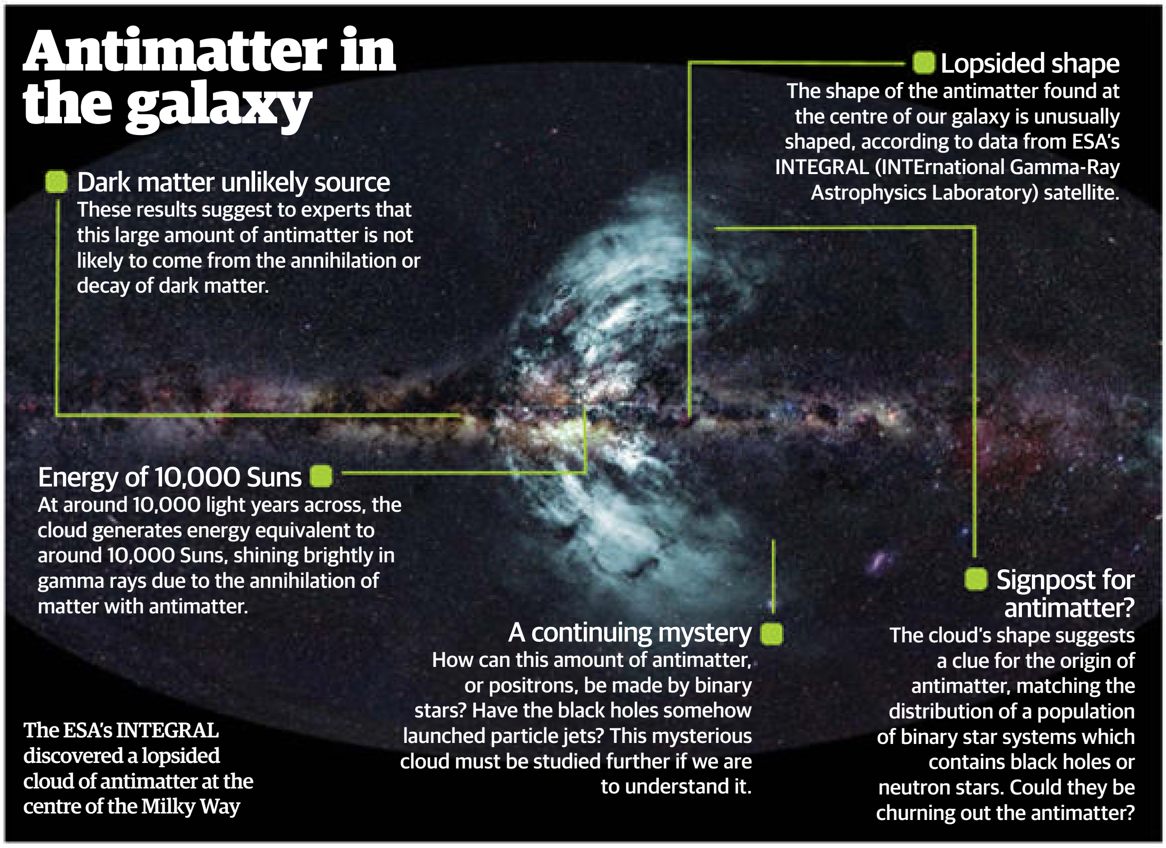
2 It could be used as fuel Spacecraft might one day be powered by the annihilation of matter with antimatter. NASA believes that the amount of antimatter required to supply power for an engine for a one-year trip to Mars could be a millionth of a gram, providing huge thrust while being a very efficient form of propulsion.

3 For medical purposes "Practical applications of antimatter are mostly in Positron Emission Tomography, which is revolutionising many medical fields," says Fajans. With physicians using beams of electrons, protons, neutrons or photons as well as chemotherapy, could a beam of antimatter eliminate cancer cells?

4 Possible interstellar travel Using antimatter to voyage between the stars is currently not possible. "Making macroscopic quantities of antimatter would require all of the Earth's energy production for thousands of years," says Fajans. However, if we could create enough antimatter, we could propel starships through the cosmos.

5 Using antimatter to probe dark matter Cosmic rays emanating from the outer reaches of the universe carry an excess of antimatter thought to be directly related to the extremely elusive dark matter. It is believed that the high amount of positrons is a result of when two particles of dark matter collide and annihilate.

Antimatter in the galaxy



The ESA's INTEGRAL discovered a lopsided cloud of antimatter at the centre of the Milky Way

you would get back, so that's a loser – that's not what you want from an energy source," states Hangst. "If some antimatter flew by and you could get a hold of it, that would be an energy source, but as far as producing it on Earth, that's just not even close."

Sadly, that means we may have to forget about antimatter-powered starships, for the moment at least. However, particle accelerators are not the only places where we can find antimatter. In 2011, 160 nanograms of antiprotons were discovered trapped in the Van Allen radiation belts above Earth, with similar amounts expected to exist in the magnetically organised radiation belts of other planets, including up to 260 nanograms around Saturn. Yet this is still a very tiny amount – add it all up and it still doesn't even come to a gram.

In the same year, astronomers announced that the Fermi Space Telescope, which observes the universe in gamma rays, had detected antimatter not coming from space, but streaming into space from above thunderstorms in Earth's atmosphere. Fermi detected high-energy gamma rays at just the right energy to indicate they were created when an antimatter particle annihilated a matter particle.

"Thunderstorm electric fields accelerate electrons to high energies," explains Professor Joseph Dwyer of the Florida Institute of Technology. "These electrons make gamma rays, which then pair-produce electrons and positrons, which are the antimatter version of the electron. The positrons may play an important role in the electrical properties of thunderstorms – it has been quite surprising how common positron production is in our atmosphere and how the positrons can actually be important for understanding thunderstorms and lightning."

> "Understanding antimatter is important to our very existence" **Joel Fajans, University of California**

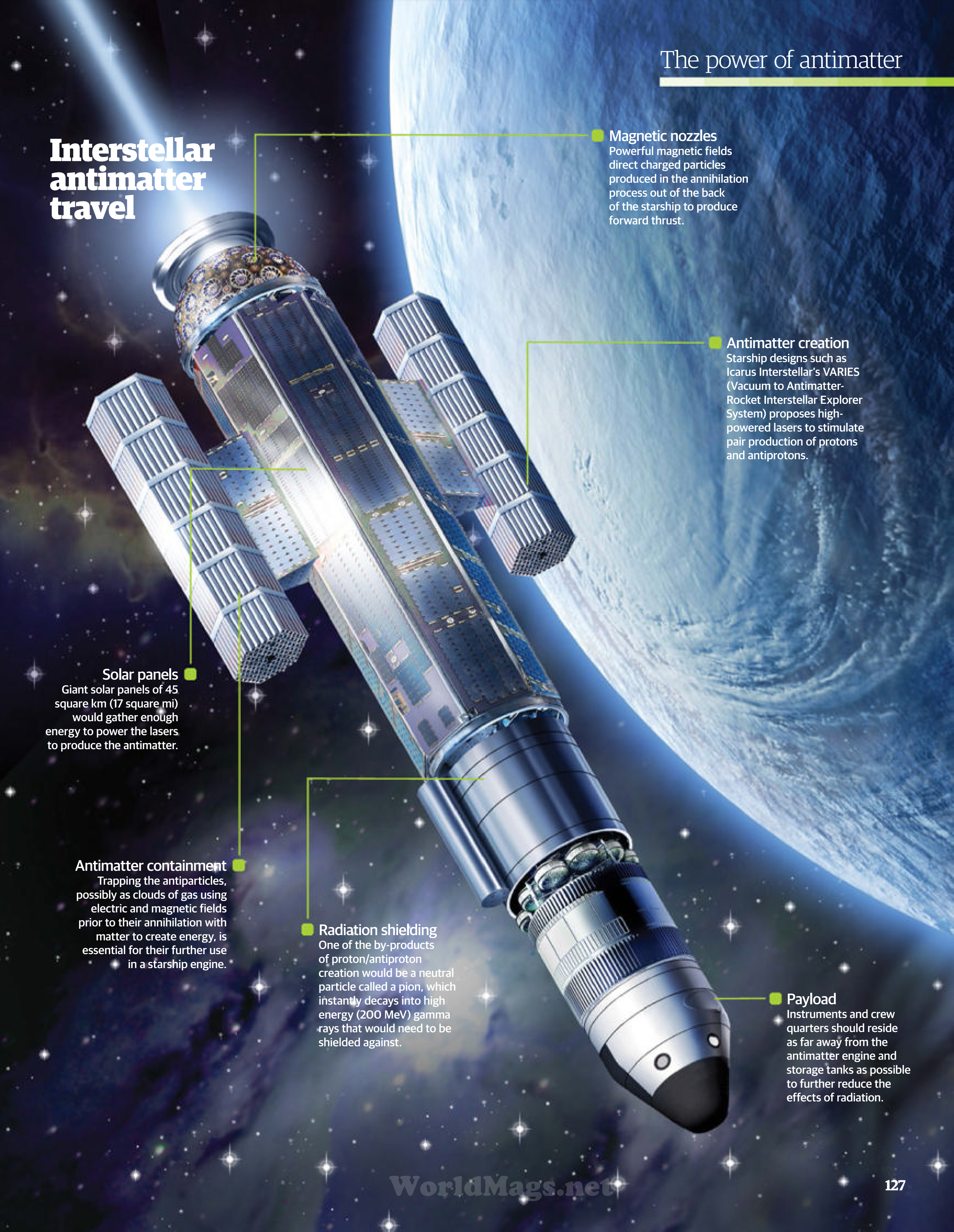
Fermi was actually expecting to see gamma rays from matter-antimatter annihilation near the centre of the galaxy, as was its European counterpart, the INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL), which discovered a lopsided cloud of positrons in the galactic centre where annihilation is taking place and producing gamma rays with energies of around 511,000 electronvolts. Meanwhile the state-of-the-art Alpha Magnetic Spectrometer (AMS) on board the International Space Station is searching for antimatter in cosmic rays.

So it seems we are really starting to make headway in our quest to solve the mysteries of matter and antimatter and ultimately the grand mystery of why the matter-dominated universe as we know it exists at all.

"There's lots going on," says Hangst. "It's a very interesting time to be working in this field because we are getting more and more capabilities. At CERN we are studying antimatter to see if it behaves in the same way as matter; that's a long-term project. We're also looking for matter/antimatter asymmetry – does antimatter somehow behave different to what the laws of physics describe for matter? We'd like to study the spectrum of antihydrogen and compare that with what we have measured in hydrogen, or look at how antimatter behaves in a gravitational field. So those are the two big things: is antihydrogen quantum mechanically the same as hydrogen and does it fall up or down in gravity?"

The answers might unlock the secrets of the expanding universe and we could be extremely close to doing just that.

Interstellar antimatter travel



Magnetic nozzles
Powerful magnetic fields direct charged particles produced in the annihilation process out of the back of the starship to produce forward thrust.

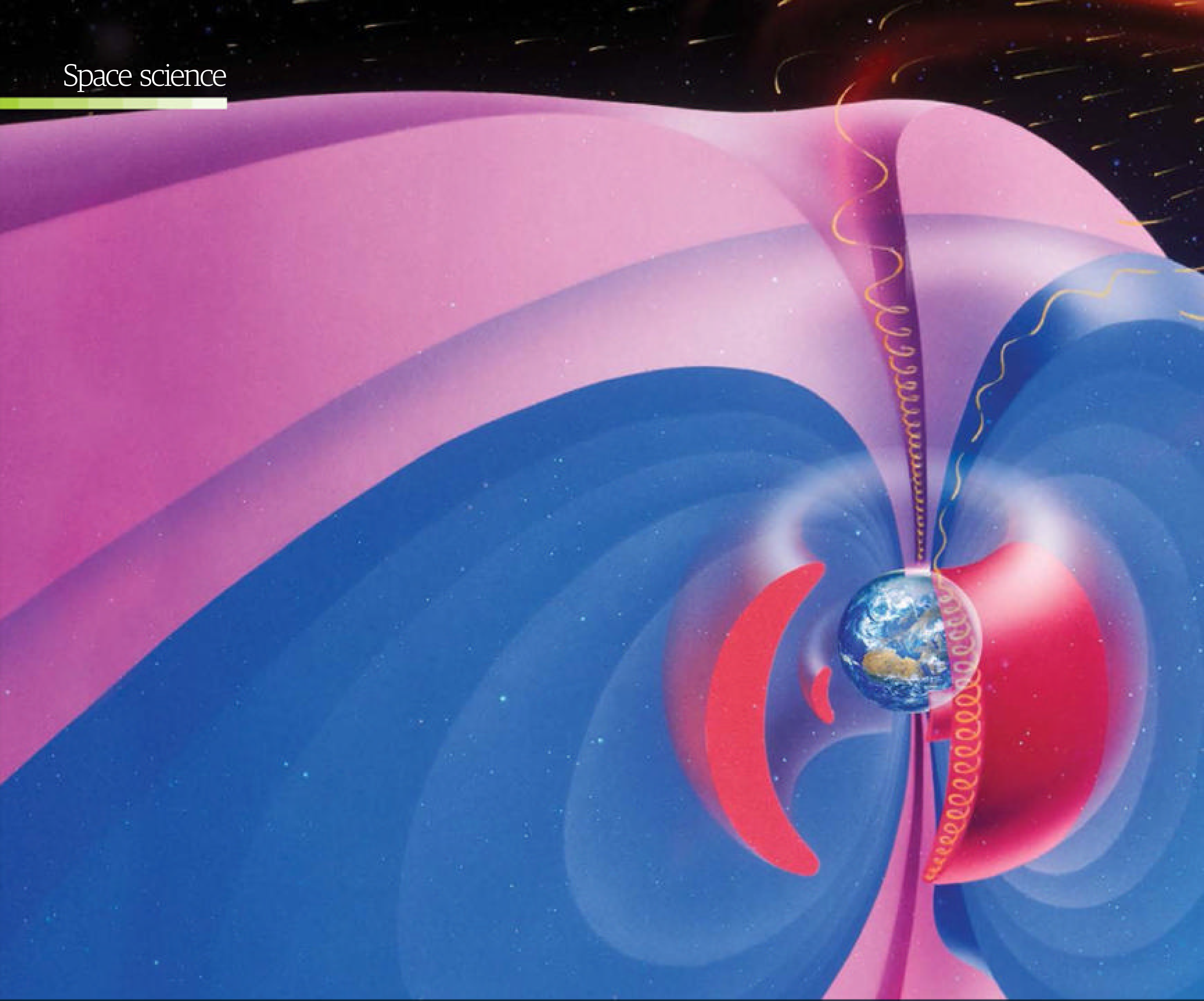
Antimatter creation
Starship designs such as Icarus Interstellar's VARIES (Vacuum to Antimatter-Rocket Interstellar Explorer System) proposes high-powered lasers to stimulate pair production of protons and antiprotons.

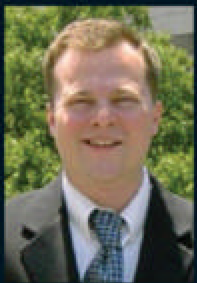
Solar panels
Giant solar panels of 45 square km (17 square mi) would gather enough energy to power the lasers to produce the antimatter.

Antimatter containment
Trapping the antiparticles, possibly as clouds of gas using electric and magnetic fields prior to their annihilation with matter to create energy, is essential for their further use in a starship engine.

Radiation shielding
One of the by-products of proton/antiproton creation would be a neutral particle called a pion, which instantly decays into high energy (200 MeV) gamma rays that would need to be shielded against.

Payload
Instruments and crew quarters should reside as far away from the antimatter engine and storage tanks as possible to further reduce the effects of radiation.





Looking for antimatter

Jim Bickford of Draper Laboratory, Massachusetts, who found a belt of antimatter naturally occurring around Earth in one of our planet's Van Allen radiation belts, tells us about his findings

Scientists have spent billions building colliders that make a few micrograms of antimatter, yet you've found it around the Earth. How does it get there?
Antimatter forms when atomic particles travelling near the speed of light collide with one another and convert their energy of motion into matter. If they are travelling fast enough, a process called pair production creates a regular particle and its antiparticle by converting the kinetic energy of motion into mass. Outside of particle colliders, there are few places on Earth where there is enough energy to create antimatter. The Earth is constantly being bombarded by high energy cosmic rays which are formed outside the Solar System. When these cosmic rays strike our atmosphere, their energy of motion can be converted into antimatter. Most of it gets lost in the atmosphere, but a small fraction bounces back into space and gets caught in the Earth's magnetic field.

Is there enough antimatter to do anything with?
The amount of antimatter trapped around Earth is comparable to the amount of material in a speck of dust. This may sound like an incredibly small amount, but antimatter has unique properties which can make this very useful for a number of applications. In particular, when matter and antimatter come into contact, they annihilate and their mass is converted into energy. Proposed applications include medical treatments, non-destructive material testing, fundamental physics and, of course, spacecraft propulsion. It would take hundreds of kilograms to propel a spacecraft to another star if used like a traditional rocket fuel.

The Van Allen belts, discovered in 1958, are two large areas of radiation surrounding the Earth

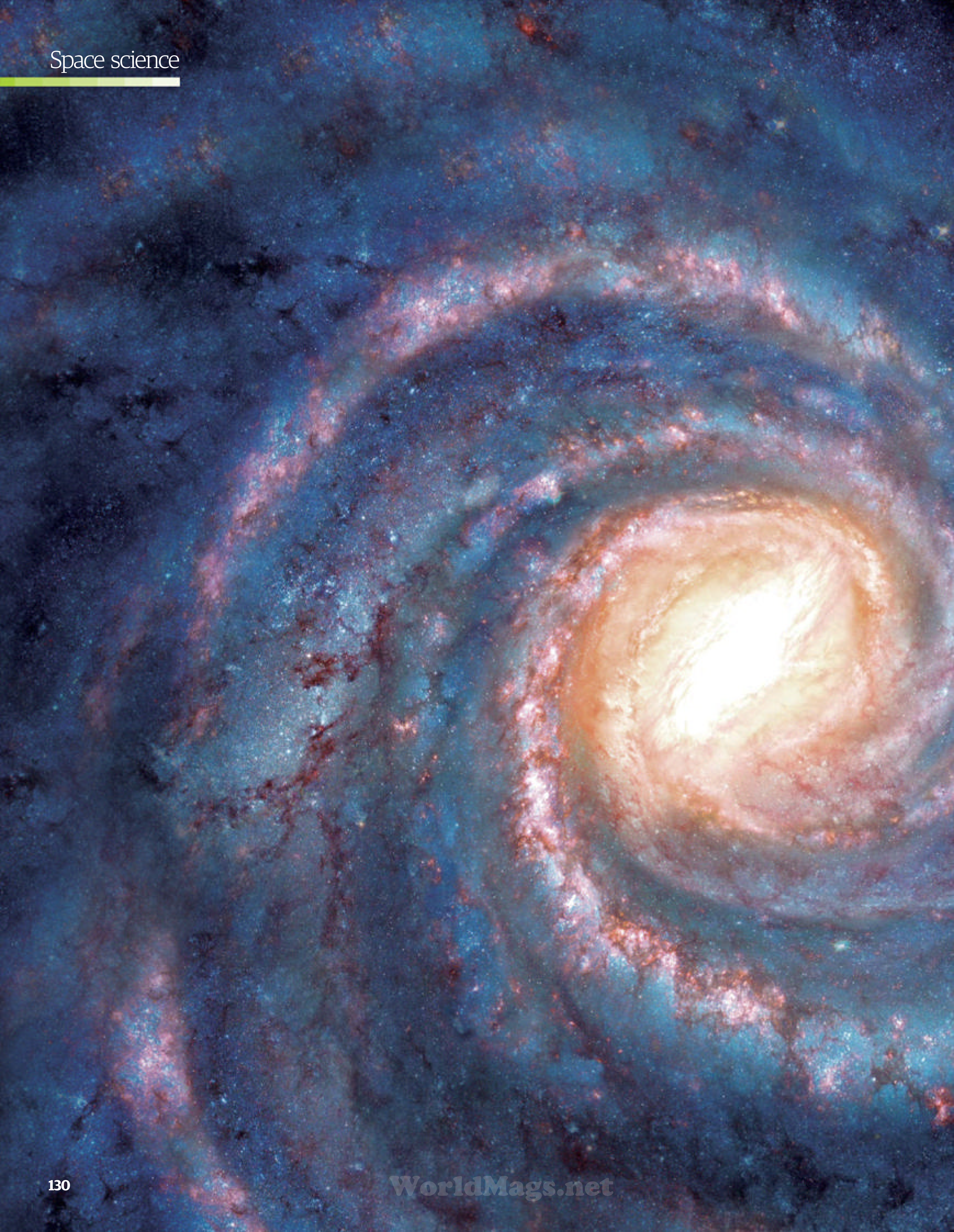
Can we collect the antimatter?
The challenge has always been how to collect enough antimatter and then store it for use since it is spread so diffusely in space and it will annihilate when it comes into contact with ordinary matter. As part of my NASA Institute for Advance Concepts (NIAC) programme, we looked at how you could use large magnetic fields around spacecraft to funnel and collect the antimatter in space. The magnetic field can then be used to store what is collected until it is ready for use. The spacecraft could basically mine the antimatter from space and then use it to propel itself.

Do you think antimatter can be found around other planets?
The amount of antimatter around Earth is minuscule. However, there is significantly more in other parts of the Solar System. During the NIAC study, we evaluated each of the planets and found that Saturn was the best place for antimatter to collect. I originally assumed that the biggest planet, Jupiter, would have the most antimatter. However, Jupiter's magnetic field was too strong and it reduced the flux of cosmic rays from striking the atmosphere. The rings of Saturn, however, have just the right geometry and composition to create antiprotons, and the magnetic field works to trap it where it can then be theoretically collected for study.

Why is antimatter only in very short supply?
The unique properties of antimatter are what make it difficult to create and store. It contains an incredible amount of energy, which also means that it takes an exorbitant amount of energy to create. It would take years of electrical output from a large nuclear plant to create the energy in a kilogram of antimatter. Once you solve the production issue, you have the problem of how to store a material that will annihilate when it comes into contact with the walls of its container. When you calculate how inefficient it is to create and store, it becomes clear that it is impractical, if not impossible, to collect large quantities of antimatter.

Can studying antimatter help us to understand new things about the universe?
Research in this area is part of a broader framework that could help fundamental science and our understanding of the universe. Antimatter is central to some of the Holy Grail problems of physics, such as the nature of dark matter and why matter dominates over antimatter.

"Proposed applications include medical treatments, fundamental physics and, of course, spacecraft propulsion"

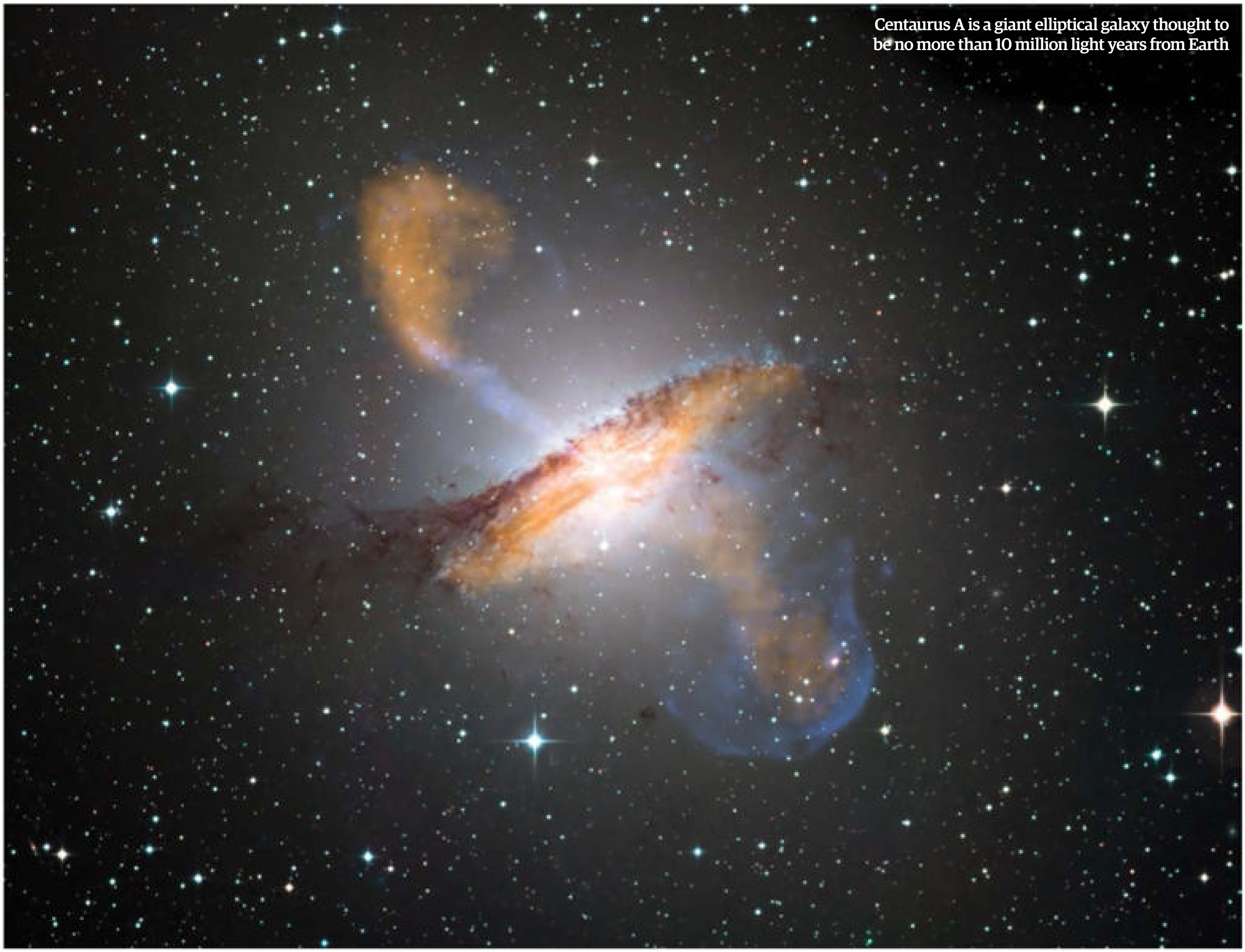


Super galaxies

They're the biggest galaxies in the universe – enormous star clouds many times the size of the Milky Way. So how do giant elliptical super galaxies form, and what influence do they have on the universe around them?

Imagine a galaxy so large that, if it took the place of the Milky Way, it would not only engulf our galaxy's immediate satellites like the Magellanic Clouds, but also swallow up the giant Andromeda spiral 2.5 million light years away. The idea of a monster on this scale might seem outlandish, but in fact there's just such a giant 1 billion light years from Earth, in the constellation of Virgo. IC 1101 is the elliptical super galaxy at the heart of the Abell 2029 galaxy cluster – a huge ball of red and yellow stars with an incredible six million-light year diameter.

Giant ellipticals, sometimes nicknamed super galaxies, are the biggest and most massive galaxies in the universe, as Ryan Hickox, assistant professor in the Department of Physics and Astronomy at Dartmouth College, New Hampshire, explains: "They tend to be found in the centres of large-scale structures, either groups or clusters of galaxies, and the largest ones have masses around a trillion times the mass of the Sun, which is around ten times more than spiral galaxies like our own Milky Way." Hickox has dedicated much of his career to understanding


Centaurus A is a giant elliptical galaxy thought to be no more than 10 million light years from Earth

these giants – their properties, distribution and, above all, the mysteries of their formation.

As their name suggests, elliptical galaxies are ball-shaped collections of stars. While most of the stars in spiral galaxies like our own Milky Way orbit around a flattened disc, the stars in ellipticals are more randomly inclined. The result is a galaxy that appears to be more or less elongated or elliptical along a particular axis. Small elliptical galaxies vary in size from around 20 to 50,000 light years across, but giant ellipticals can be several hundred thousand light years wide. Even bigger 'cD' galaxies have huge, diffuse outer layers that may be a million or more light years across.

"One of the key properties of elliptical galaxies is that they have very old stars, most of which formed probably only a few billion years after the Big Bang, and right now they have very little cold, dense, star-forming gas in them, so they have very little ongoing star formation," explains Hickox. It's this lack of star formation that leaves ellipticals dominated by red and yellow stars – these sedate, low-mass stars have lifetimes of many billions of years, while hotter white and blue stars live and die on much shorter timescales, and so die out relatively rapidly if star formation stops. "In a galaxy like the Milky Way, you might have one Sun-like star being born every year," Hickox continues, "but a giant elliptical could be ten times more massive, and yet have a star formation rate ten times slower. One of the major questions about giant ellipticals is why they don't have this gas."

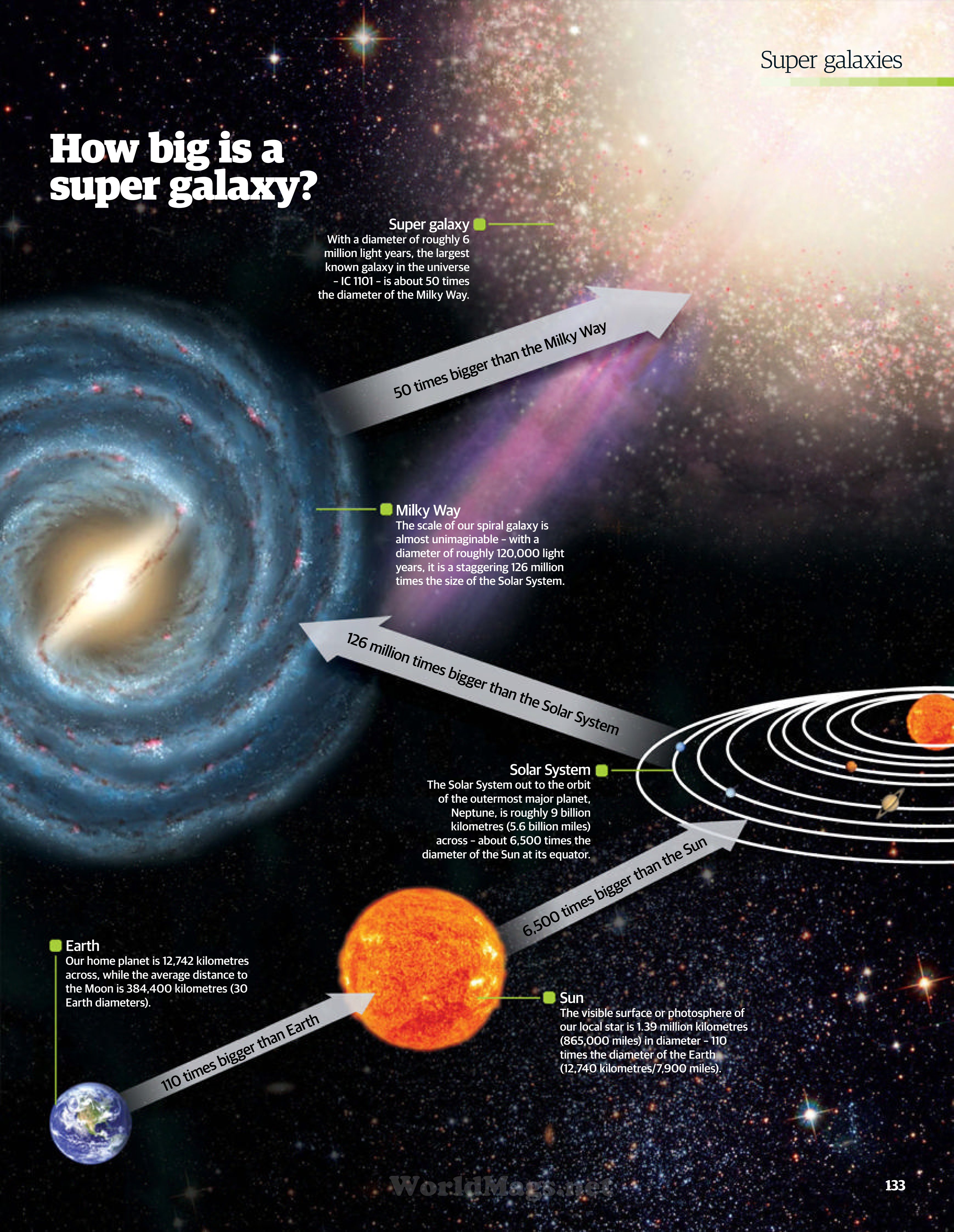
As well as trillions of individual stars, super galaxies are often surrounded by large numbers of globular star clusters. These compact balls of up to a million stars look rather like miniature elliptical galaxies in their own right, and are also dominated by old red and yellow stars. Around 150 of these clusters orbit in and around our Milky Way galaxy, but giant ellipticals such as Messier 87 (one of the closest super galaxies to Earth, some 54 million light years away at the heart of the Virgo Cluster) may be accompanied by many thousands of globulars.

While smaller ellipticals are found throughout the universe, the real monsters are only ever found near the centre of large galaxy groups and clusters, where their gravitational influence makes a major contribution to holding the cluster together. Here, X-ray observations show that they are surrounded by vast clouds of gas, heated to many millions of degrees by tidal forces between the cluster galaxies.

"We think the reason why that gas is hot is because it's sitting in the gravitational well of the

"They have very old stars, most of which formed probably only a few billion years after the Big Bang"
Ryan Hickox

How big is a super galaxy?



Super galaxy

With a diameter of roughly 6 million light years, the largest known galaxy in the universe – IC 1101 – is about 50 times the diameter of the Milky Way.

Milky Way

The scale of our spiral galaxy is almost unimaginable – with a diameter of roughly 120,000 light years, it is a staggering 126 million times the size of the Solar System.

Solar System

The Solar System out to the orbit of the outermost major planet, Neptune, is roughly 9 billion kilometres (5.6 billion miles) across – about 6,500 times the diameter of the Sun at its equator.

Earth

Our home planet is 12,742 kilometres across, while the average distance to the Moon is 384,400 kilometres (30 Earth diameters).

Sun

The visible surface or photosphere of our local star is 1.39 million kilometres (865,000 miles) in diameter – 110 times the diameter of the Earth (12,740 kilometres/7,900 miles).

Anatomy of IC 1101 – the biggest galaxy known to man

whole cluster, which may have a mass a thousand times or more than the central galaxy. But one thing that's not been clear is where that gas actually comes from – has it fallen in from outside, or is it a hot 'atmosphere' produced by evolving stars inside the galaxy? You can think of the hot gas in the system as being bound to the galaxy cluster as a whole, but it's an open question how much is associated with the galaxy itself."

At the heart of every giant elliptical lies an enormous supermassive black hole that acts as the galaxy's gravitational anchor. These are the largest black holes in the universe – super-dense regions of space containing the mass of a billion or more Suns squeezed into a volume the size of the Solar System. They hold the key to understanding the way that super galaxies form and evolve, and as a result have become the focus of intense research.

Learning about the black hole in the first place, though, can be a tricky business. In some cases, where the hole is actively feeding on its surroundings, it may give itself away through X-ray emissions or by ejecting high-speed jets of particles (jets that are now thought to play a key role in preventing the cooling of the surrounding hot gas and choking off the formation of new stars. In other galaxies, however, the black hole may be dormant: invisible by its very nature, it gives itself away through its gravitational influence.

"The most direct way to observe the presence of a black hole in a galaxy is by watching the orbits of stars in the centre and inferring that the mass that has to be present in order to hold the stars in their orbits," explains Hickox. "The best example of this is from our own spiral galaxy, where we can resolve individual stars going around the central black hole, but other galaxies are too far away for us to resolve the orbits of individual stars. What you can do instead is take spectra of the galaxy's central regions." By splitting the light into a spectrum of different colours and analysing how these change from one side of the centre to the other, it's relatively simple to work out the speed at which the stars are moving.

Even this is only possible for relatively nearby galaxies, but Hickox points out one way that the method can be extended. "You can use this kind of technique a bit further if a galaxy has a feature called a maser – a beam of microwave emission that's produced by a chain reaction in the galaxy's gas. Sometimes this will create individual spots near the

"You can use this kind of technique a bit further if a galaxy has a feature called a maser: a beam of microwave emission"
Ryan Hickox

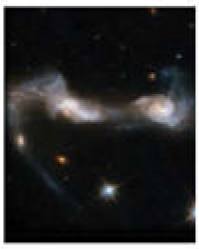
Formation of a giant galaxy

According to the most successful theories, elliptical super galaxies originate in the collision of two or more gas-rich disc-shaped galaxies, followed by further mergers throughout the galaxy's history. These simulations track the evolution of a super galaxy over several billion years.

1. Gas-rich discs

The light from disc galaxies is dominated by young, bright and short-lived stars that are continuously created in disc regions filled with star-forming gas and dust, and older red and yellow stars in a comparatively gas-poor hub.

2. In collision

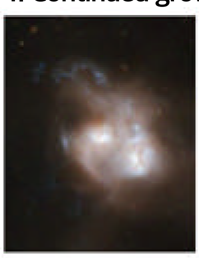


When galaxies collide, direct hits between stars are rare, but tidal forces disrupt the spiral arms and cause them to unwind. Clouds of gas, however, undergo head-on collisions that can heat them up and drive gas out into the galaxy's halo.

3. Birth of an elliptical

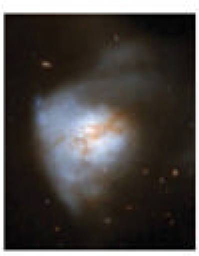
Stripped of the cool gas that can help to form new stars, the galaxy now consists of older, long-lived stars that are left in chaotic orbits around the nucleus, which contains a large supermassive black hole.

4. Continued growth

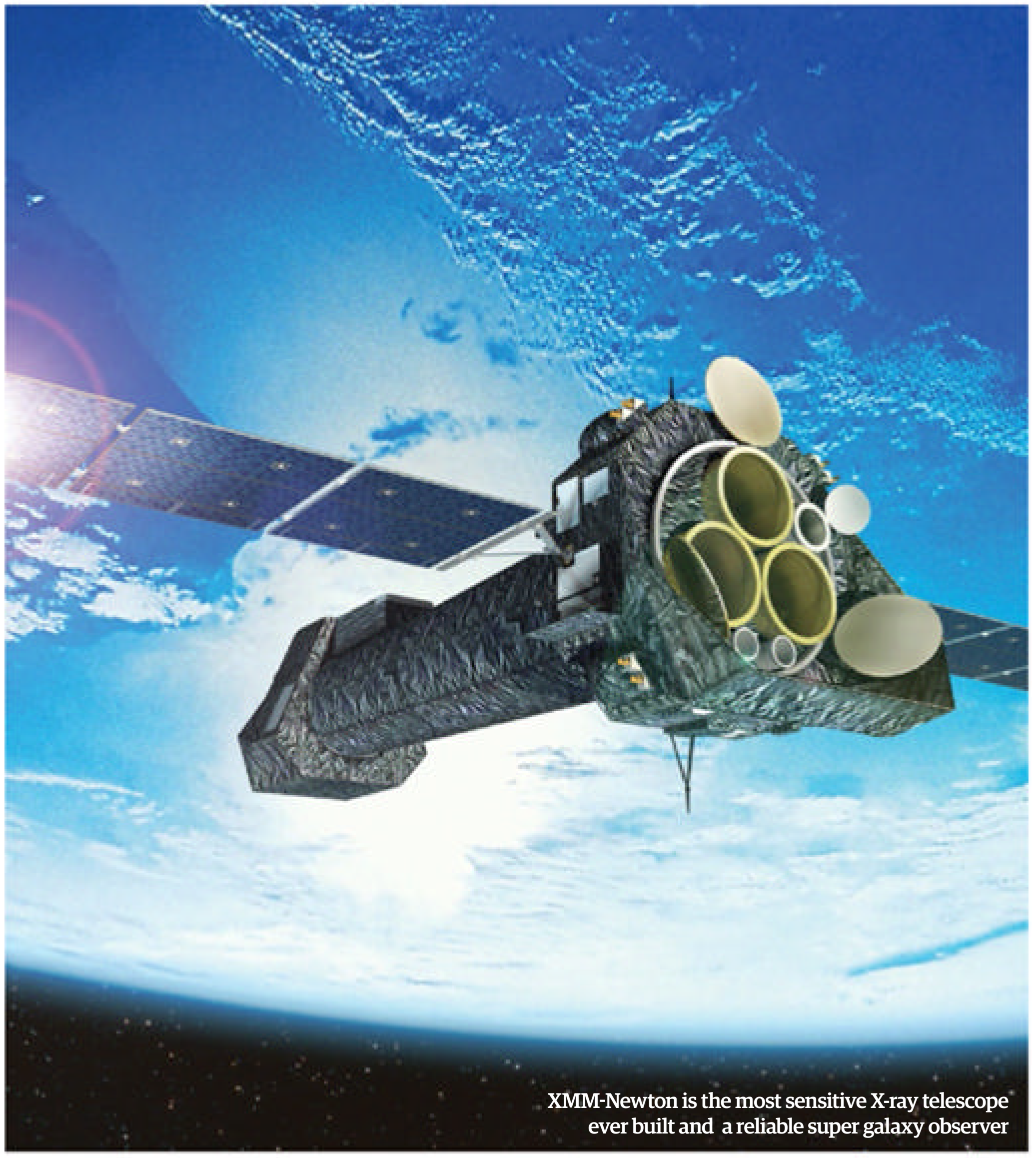


The newly formed giant's enormous gravity leads to more frequent collisions, in which they may absorb further disc galaxies, cannibalise small irregular galaxies, or undergo 'dry' mergers with other gas-poor galaxies.

5. Central member



Today, super galaxies are found at the centre of highly evolved, dense galaxy clusters. Depending on their extent and density, they can be classed as either giant elliptical galaxies or cD galaxies.



XMM-Newton is the most sensitive X-ray telescope ever built and a reliable super galaxy observer

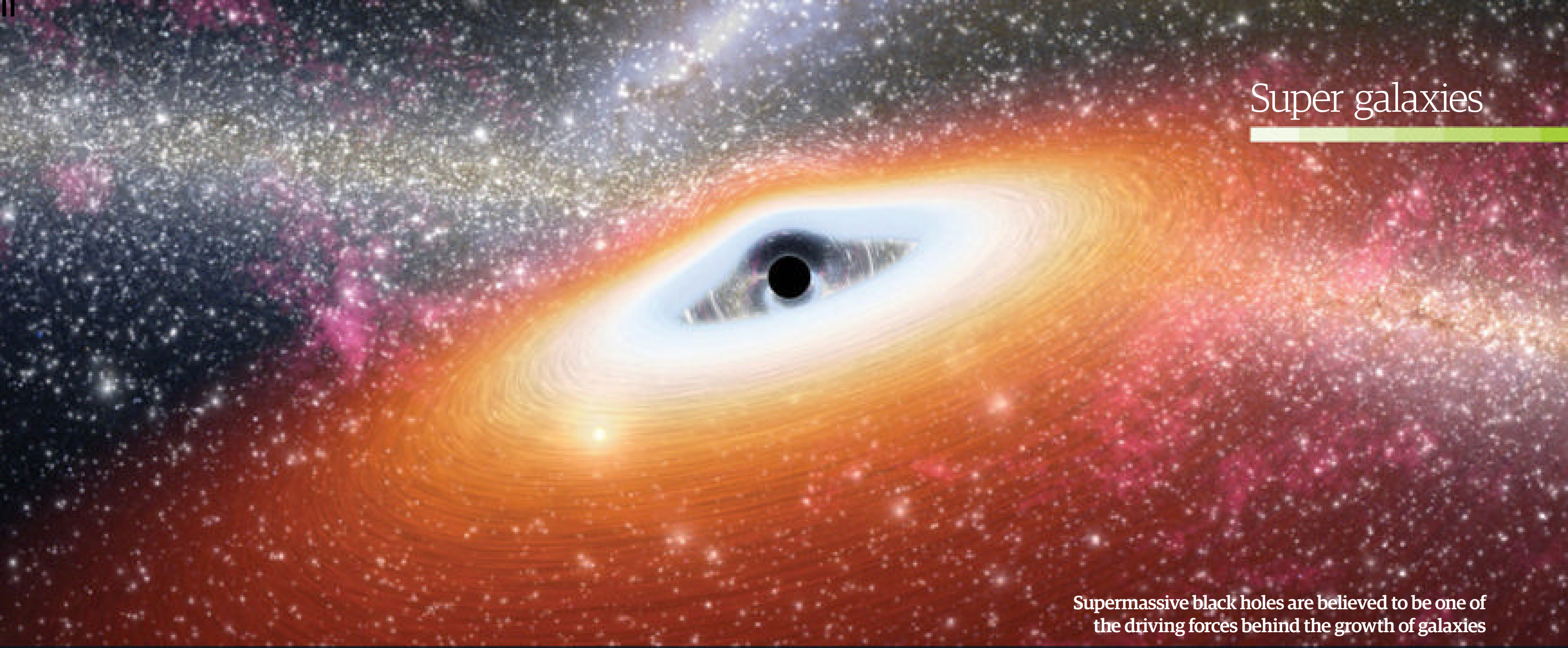
"So in other words, we know what galaxies those violent early galaxies will turn into because we know how their dark matter halos will evolve"
Ryan Hickox

centre of a galaxy, and if we can trace the motion of the maser around the centre, that can give us another handle on the mass of the central black hole."

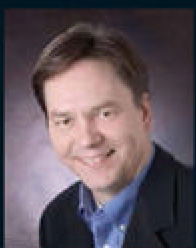
Researchers have used a variety of more complex methods and rules of thumb to measure the mass of black holes in even more remote galaxies, and a remarkable pattern seems to have emerged from their results. The size of the central black hole seems to increase in line with the mass of visible matter in the galaxy, estimated from the combined brightness of its stars.

This evidence has given rise to the most popular model for the formation of elliptical super galaxies – the idea that they formed from the collision of smaller, gas-rich systems whose black holes combine together at the same time, accompanied by intense bursts of star formation and other activity. This model explains many of the distinctive features of super galaxies, ranging from their stellar populations to their lack of gas and dust and location in the heart of dense galaxy clusters. It even offers an explanation for the hot gas clouds in the centre of clusters.

The major problem for astronomers, however, is that it's impossible to see this process in action on a short timescale – the best we can hope for is to see 'snapshots' of different stages in the process. How can we be certain that distant interacting or active galaxies (existing in earlier, more turbulent stages of cosmic history and whose light may have taken billions of years to reach Earth) are evolving to become present-day super galaxies? Recent studies by Hickox and his colleagues may provide



Supermassive black holes are believed to be one of the driving forces behind the growth of galaxies



Probing the secrets of galactic growth

Brian McNamara, Professor of Astrophysics at the University of Waterloo in Ontario, Canada, explains how galaxies can grow to such a tremendous size

Why is it important to study the brightest galaxies at the centres of galaxy clusters?
What's interesting about studying the brightest cluster galaxies is that we can see the normal processes that occur at the centres of all elliptical galaxies in great detail, because everything is amped up - we see these powerful jets coming out of supermassive black holes. The black holes are bigger, the jets are more powerful, and the mass of gas surrounding them is larger, so given the instrumentation we have, we can study this process we call feedback in tremendous detail.

Can you explain what the feedback process involves?
The notion of feedback is pretty simple - in the late-Nineties we discovered there's a remarkable relationship between a galaxy's total mass and that of its central, supermassive black hole. Their ratio is nearly constant, which implies that something is governing the growth of both - and maybe it's the black hole doing it. The notion that something so tiny could regulate the growth of the entire galaxy is remarkable and raises all kinds of other issues - how do you regulate the matter falling into the black hole, which is what generates the energy, and how does it 'know' to create enough energy to prevent all the surrounding gas collapsing and forming stars?

How can you study the mechanisms involved?
The key observations involve taking X-ray images of galaxies and clusters, with telescopes like the Chandra X-ray Observatory and the XMM-Newton observatory. When you take a picture of a cluster in X-rays, you see X-rays coming from the hot gases.

These gases are hot because the gravitational forces are so large that the gases move about and collide with each other at enormous speeds, creating heat. When we look carefully we find giant holes in the X-ray emission, and these holes were blasted out by jets of magnetic fields and particles - electrons and protons - launched from the vicinity of the black holes. The holes can be huge - thousands to tens of thousands of light years across.

Enough energy is pumping out of these black holes to keep the gas at a high temperature and prevent it from cooling. The energy is then released when small amounts of the gas do cool and fall on to the black hole - that's why it is what's known as a feedback effect.

So how widespread is this process?
There is indirect evidence to suggest that it's prevalent - it's going on in most or all giant elliptical galaxies, and some theoretical studies have shown that when you include this in your models of galaxy formation, you can actually describe the overall luminosities and sizes of galaxies today. We've found 50 or more of these things now, pumping out energy on a variety of scales. Messier 87 is the nearest of these systems, but it's actually producing energy at a quite low rate - the biggest one we've found is nearly a million times more powerful. It turns out the amount of energy that's being pumped in is just about the right amount of energy you need to quench star formation.

Where do you see this work going next?
The thing we're really excited about at the moment is ALMA [the Atacama Large Millimeter/submillimeter Array]. My group got early science time on the project, and we found something that surprised the hell out of us. We had assumed that we'd see radio emissions from gas falling in to feed star formation - at a lower rate than normal, because of the feedback effect, but still happening. But when we got our first observations, we actually saw this cool molecular gas flying outwards. We hadn't expected that, because the molecular gas is very dense - thousands to a million times denser than the gas associated with these bubbles. Trying to move molecular gas with the hot gas would be like trying to move a boulder with a garden hose. If this turns out to be happening in a lot of ellipticals, the feedback mechanism has to be coupled to the cold gas as well. It's the cold gas that ultimately fuels the black hole and star formation, so we're seeing an extra cog in this chain. Feedback is still troubling, because it's hard to make it work conceptually and theoretically, but everywhere we look, we see it happening. I think nature is teaching us something new about the physics of these black holes.

"We've found 50 or more of these things now, pumping out energy"

the missing link. They have been looking at the relationship between the central supermassive black holes of giant galaxies and unseen 'dark matter' that does not interact with light but forms huge extended halos around the visible galaxies. Vastly outweighing visible matter, this material has an important role to play in the birth and evolution of any galaxy, but can only be detected through its gravitational influence on visible objects around it.

"We can estimate the mass of galaxy halos by measuring the spatial clustering of the visible galaxies," Hickox explains. "We know that galaxies with more massive halos bunch together more in space [due to their greater overall gravity], so by measuring how tightly clustered the galaxies are, we can get an estimate of how massive the typical halo is that these galaxies live in. A lot of my work has involved looking at distant, growing systems and asking what are the masses of the halos that those galaxies reside in."

It turns out that by estimating the size of halos in distant galaxies, Hickox can predict how those galaxies will look in the future: "The interesting thing is that, because the physics of gravity is fairly well understood, then if you have a halo that's a few billion light years away, you have a pretty good idea of what that halo's going to evolve into. If we know how massive the halo of some distant active galaxy is, we can estimate the mass of the halo at the present time. The same goes for big powerful starburst galaxies. What we've found is that these halos are consistent with them living in medium-to-large-scale galaxy groups today, and that's exactly where we find massive elliptical galaxies today. In other words, we know what galaxies those violent early galaxies will turn into because we know how their dark matter halos will evolve."

If this seems like conclusive evidence of how modern elliptical galaxies formed, it's not end of the story. "There's still uncertainty over how much different types of mergers contribute to the process," points out Hickox. "Really big galaxies like Messier 87 probably had a different history from smaller ellipticals, but the general model still stands up."

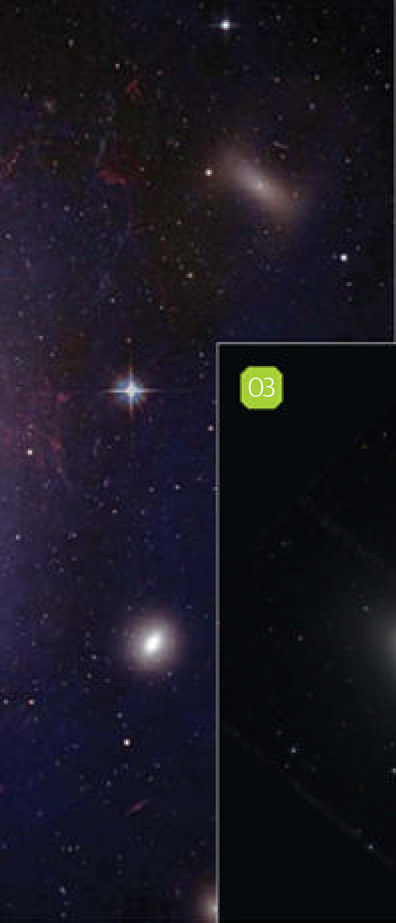
For the most enormous galaxies in densely packed clusters, such as IC 1101, the story is probably quite different again. It seems that there's certainly plenty we are still to learn and understand about the biggest galaxies in the universe.

"Really big galaxies like Messier 87 probably had a different history from smaller ellipticals, but the general model still stands up"
Ryan Hickox

5 super galaxies

1. Perseus A
Size: 250,000 light years across
Mass: 20 Milky Ways
This complex super galaxy consists of a cD galaxy with an active black hole ejecting bubbles of hot gas, and a foreground dusty galaxy heading towards it on a collision course.

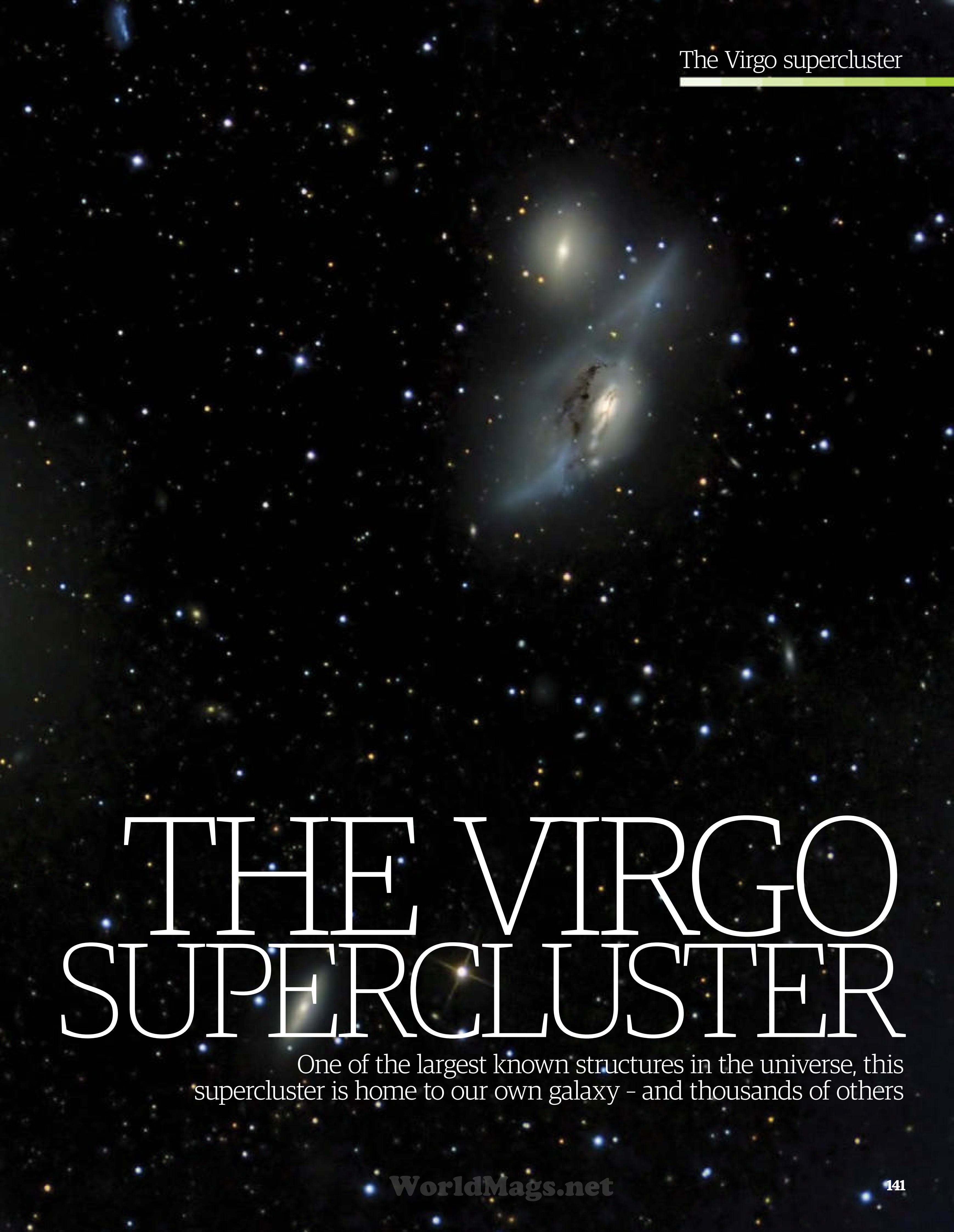
2. Messier 87
Size: 1 million light years across
Mass: 2 Milky Ways
Messier 87 is our closest cD galaxy, with active jets emerging from the region around its central black hole. Interactions with neighbouring galaxies are thought to have truncated growth of its outer halo.



3. NGC 6482
Size: 1 million light years across
Mass: 3 Milky Ways
This giant elliptical is known as a 'fossil galaxy group' – irregularities in the X-ray gas clouds around it allow astronomers to trace the original galaxies that merged to form the central giant.

4. NGC 1399
Size: 1.3 million light years across
Mass: 2 Milky Ways
A relatively small cD galaxy, NGC 1399 is orbited by around 6,000 globular clusters and has a central black hole with the mass of 500 million Suns.

5. Centaurus A
Size: 100,000 light years across
Mass: 1 Milky Way
Though relatively similar in size and mass to the Milky Way, this giant elliptical is one of the closest active galaxies to Earth. It's thought to consist of a dusty spiral galaxy in the process of merging with an older elliptical.



THE VIRGO SUPERCLUSTER

One of the largest known structures in the universe, this supercluster is home to our own galaxy – and thousands of others

While it can be difficult to visualise just how our planet fits in with the rest of the universe, it may be helpful to realise that it's just one element in a much larger picture. Much like a set of Russian matryoshka (nesting) dolls, there are numerous layers.

Our Milky Way – containing the Solar System, along with billions of other stars – is part of a group of galaxies called the Local group, located inside a larger group of galaxy groups and clusters called the Virgo supercluster (VS). A supercluster is essentially a massive group of galaxies, which in turn may be classified into groups and clusters.

This means our own galaxy is just one of thousands in the VS, which has a volume 100 billion times that of the Milky Way. Superclusters don't exist as entirely separate, uniform structures in the universe, though; instead they're grouped in what astronomers term walls, sheets and filaments. Between these there are wide expanses of mostly empty space. All together, this structure is often called the cosmic web.

The VS is named after the Virgo cluster located at its heart (located in the Virgo constellation) and has an estimated diameter of 110 million light years. Also known as the Local supercluster (LS), it's one of millions of other superclusters in the known universe. Although these are massively large structures, research shows that the VS is small when compared with other superclusters.

The VS comprises of two main structures: a disk and a spherical halo. The disk is a flattened ellipsoid, less than one megaparsec (3,261,633 light years) wide and containing nearly 70 per cent of the galaxies, while the halo contains the rest. The galaxies are grouped into substructures called clouds. In the disk nearly all of the galaxies are in 11 main clouds, while in the halo they're concentrated in about seven clouds. The Virgo cluster is considered to be the richest galaxy cluster within the VS and the Local group is located in a filament near the outer edge of the disk.

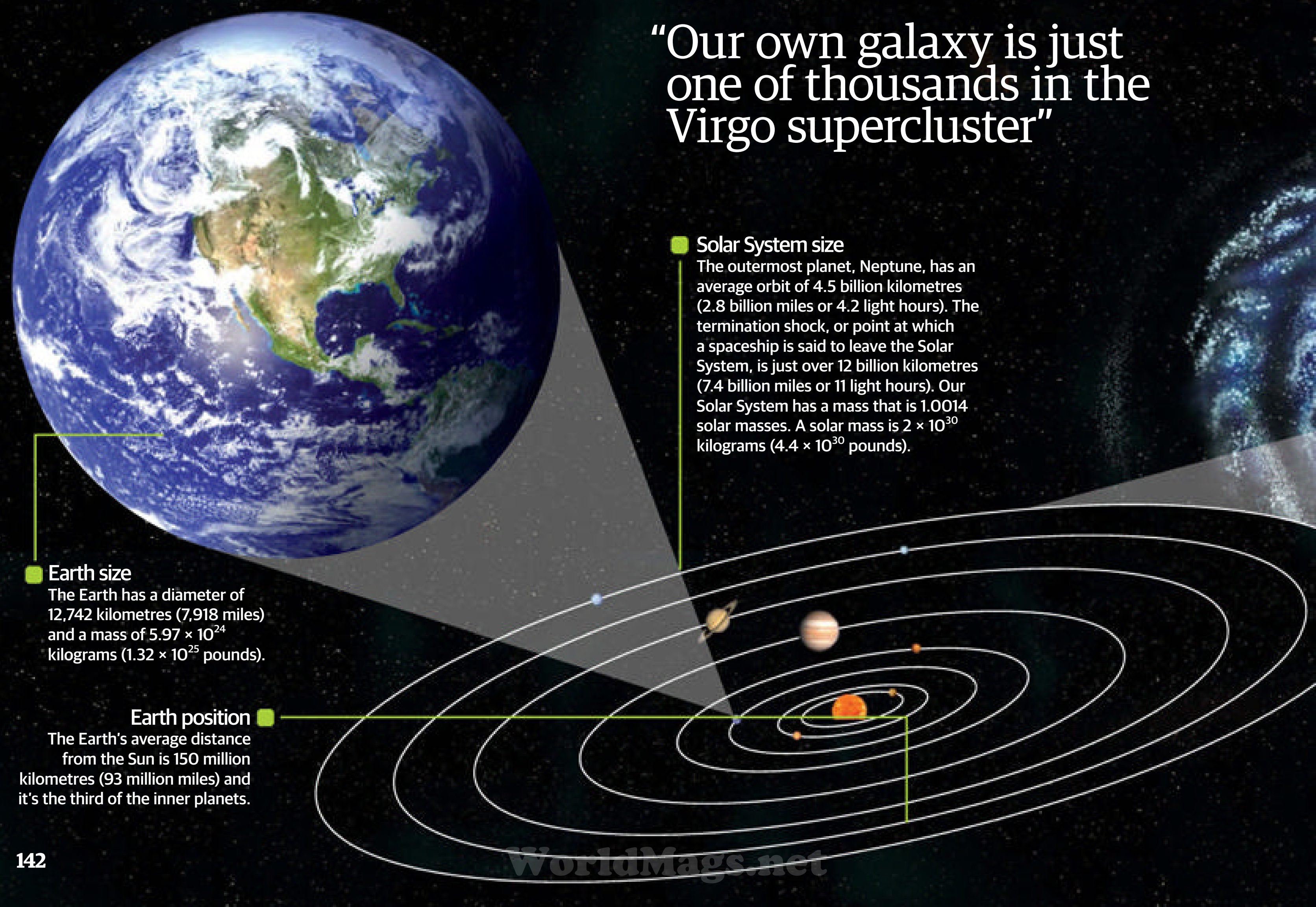
So, how does the VS stack up against other superclusters? Its closest rival is the Hydra-Centaurus supercluster, at 100 million light years long. This is sometimes separated into two distinct superclusters and is very similar to the VS in that it has one rich galaxy cluster and likely has the same number of galaxies. The next closest supercluster, Perseus-Pisces, is one of the largest known superclusters in the universe. This is a dense wall of galaxies that spans about 300 million light years and borders the Taurus Void, a large circular empty space surrounded by walls of galaxies. By contrast, the Pavo-Indus supercluster is considered rather sparse and small, with no rich galaxies at all.

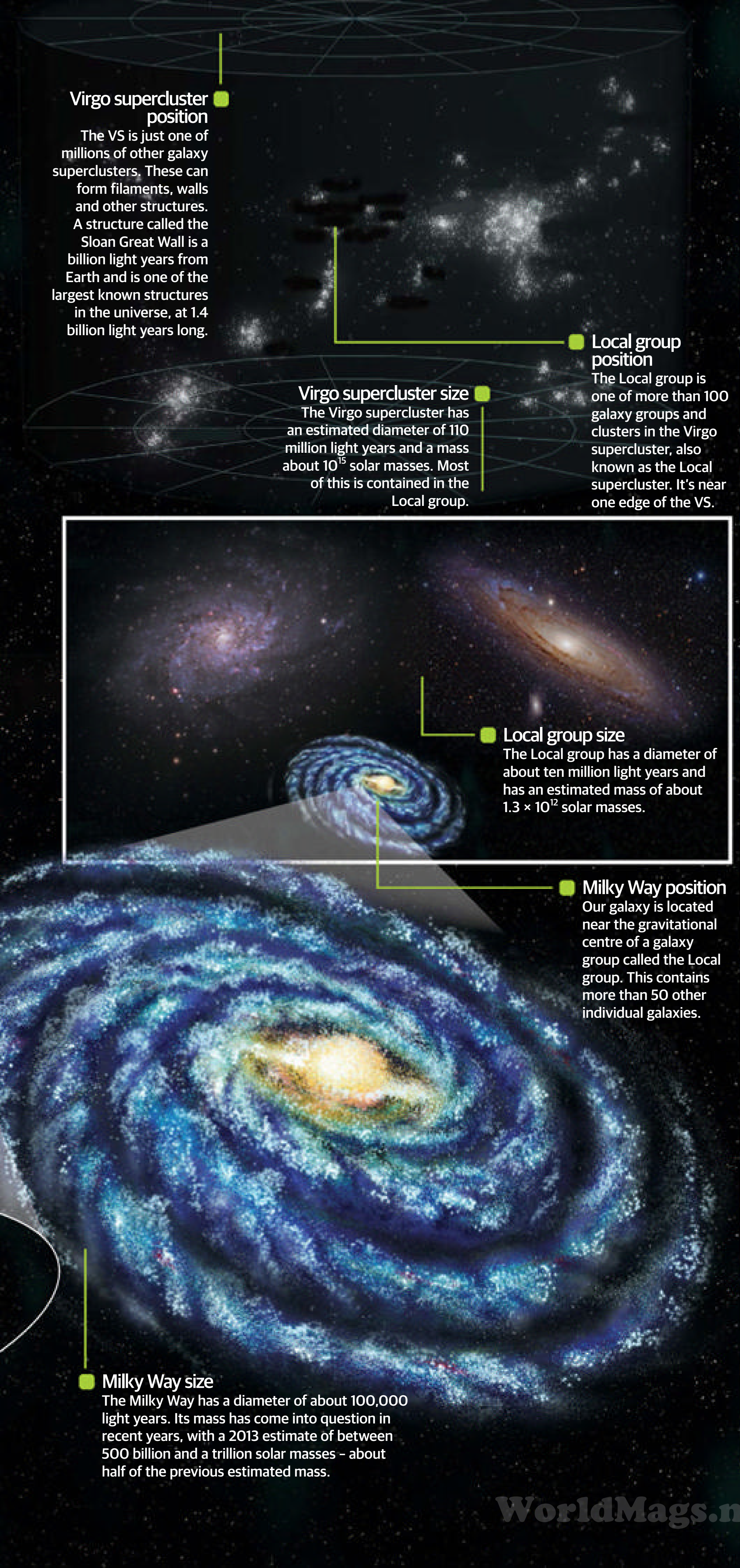
The VS, like all galaxy clusters, is bound together by gravitational attraction. There's also a whole lot of movement going on – and much of it isn't that well understood. We do know that the entire VS rotates around its centre of mass and it's also moving through space. The galaxies rotate too, as well as interact with one another. The Local group is estimated to be rotating around the centre of the VS at 400 kilometres (250 miles) per second, for instance. Two of the galaxies in the Local group, the Milky Way and Andromeda, are spiral arm galaxies that are moving towards each other at a speed of 110 kilometres (68 miles) per second. They are estimated to collide and form one huge elliptical galaxy in about four billion years.

Then there's the fact that the universe itself is expanding, so gravitational attraction is pulling all of the galaxies, galaxy clusters and superclusters towards one another. The accepted model is that this is happening equally in all directions. However, there's another mysterious force pulling on the VS (along with other local superclusters), towards the Norma cluster, moving at over 600 kilometres (373 miles) per hour.

The Norma cluster is about 220 million light years away and is the centre of a gravitational anomaly called the Great Attractor. One suggestion is that there's something beyond our observable universe doing the pulling called the dark flow.

"Our own galaxy is just one of thousands in the Virgo supercluster"





Virgo supercluster position
The VS is just one of millions of other galaxy superclusters. These can form filaments, walls and other structures. A structure called the Sloan Great Wall is a billion light years from Earth and is one of the largest known structures in the universe, at 1.4 billion light years long.

Local group position
The Local group is one of more than 100 galaxy groups and clusters in the Virgo supercluster, also known as the Local supercluster. It's near one edge of the VS.

Virgo supercluster size
The Virgo supercluster has an estimated diameter of 110 million light years and a mass about 10^{15} solar masses. Most of this is contained in the Local group.

Local group size
The Local group has a diameter of about ten million light years and has an estimated mass of about 1.3×10^{12} solar masses.

Milky Way position
Our galaxy is located near the gravitational centre of a galaxy group called the Local group. This contains more than 50 other individual galaxies.

Milky Way size
The Milky Way has a diameter of about 100,000 light years. Its mass has come into question in recent years, with a 2013 estimate of between 500 billion and a trillion solar masses – about half of the previous estimated mass.

By the numbers

110 million light years

The distance spanned by the Virgo supercluster.

7,000

The VS is about 7,000 times the volume of the Local group.

100

There are at least 100 galaxy clusters and galaxy groups in the VS – each of them containing around 50 to 1,000 galaxies.

3.2×10^6 light years

Or one megaparsec – the thickness of the flattened disk in the VS that contains most of its galaxies.

3×10^{12} solar luminosity

The VS's total optical luminosity as compared to the Sun's luminosity.

Quadrillion

The mass of the Virgo supercluster is about a quadrillion times that of the Sun's mass.

373 miles per second

The speed at which VS is heading towards the Great Attractor.

100 Billion

The volume of the VS is 100 billion times that of the Milky Way.

Inside the Virgo supercluster

Take a look inside this intricate web of galaxies and clusters spanning millions of light years across

The VS is home to more than 100 galaxy clusters and galaxy groups, but most are considered rather small and minor. The Local and Virgo are the two largest clusters – the former is located on the outskirts of the VS and the Virgo cluster is at the supercluster's centre. In addition to the Milky Way, the other major galaxies in the Local group are the Andromeda and the Triangulum galaxies. The Milky Way and Andromeda are both massive, barred (containing a central bar structure) and spiral-armed. The latter is also the larger of the two and contains twice as many stars, but it's not believed to be as massive.

Both these galaxies have numerous smaller galaxies around them – some in orbit and others just nearby – each with their own characteristics and interactions with one another. The Milky Way has between 14 and 26 small orbit galaxies, while Andromeda has at least 24. Some of these companion galaxies contain very old stars, while others are considered young by comparison and stars are continuing to form all the time. Some galaxies, such as the Large Magellanic Cloud (LMC) around the Milky Way galaxy, are considered irregular galaxies – they have no distinct shape. However, the LMC may have previously been a spiral-armed galaxy and was disturbed by interactions with the Milky Way and the nearby Small Magellanic Cloud (SMC). The LMC and SMC are also both visible from Earth. Also in orbit around the Milky Way is the object considered to have an unusually high concentration of dark matter – the Draco Dwarf galaxy.

The Andromeda galaxy can be seen from Earth because it's so bright – visible to the naked eye when it's viewed during a new Moon. It also has a very bright orbiting galaxy visible from Earth: a dwarf elliptical galaxy called M32. Astronomers believe that Andromeda's satellite galaxies mostly align on a plane that passes through the centre of the galaxy – a curious finding that doesn't mesh with the current understanding of how galaxies form.

The third largest galaxy, Triangulum, may be a satellite of Andromeda – it's an unbarred spiral galaxy and considered one of the most distant objects you can view from the Earth without a telescope or binoculars, situated at about three million light years away. As for companions, the Pisces Dwarf galaxy could be a satellite of Triangulum, but it might also be a satellite of Andromeda. In addition, secluded from both Andromeda and the Milky Way are ten additional galaxy groups.

At the heart of the Virgo supercluster is its namesake, the Virgo cluster, located in the Virgo constellation. It contains around 1,500 galaxies that distribute fairly uniformly. Within this are three subgroups, or subclumps, called Virgo A, Virgo B and Virgo C, each centring on a separate elliptical galaxy. The most dominant is Virgo A, centred on M87. This galaxy has a supergiant black hole at its centre that has a mass estimated to be 3.5×10^9 times that of the Sun, believed to be one of the highest black hole masses in the known universe. It's also apparent that the three subclumps in the Virgo cluster are merging and that the cluster is still forming. Because it's so massive, the Virgo cluster heavily influences other galaxy groups and clusters in the supercluster and slows their movement.

Although it's impossible to talk about all other galaxy groups and clusters in the VS, the M81 group is significant because it's very close to the Local group. Unlike our native group, this group is a very loose conglomeration of galaxies, some of which are so weakly bound that they don't even orbit around the centre, giving the appearance of a cloud. This makes identifying the brightest of the galaxies difficult, because it can be hard to determine which galaxies are members.

> "The Andromeda galaxy is visible from Earth because it's so bright"

This illustration depicts how a collision between the Milky Way and Andromeda galaxies might look in the night sky in about four billion years

On a collision course

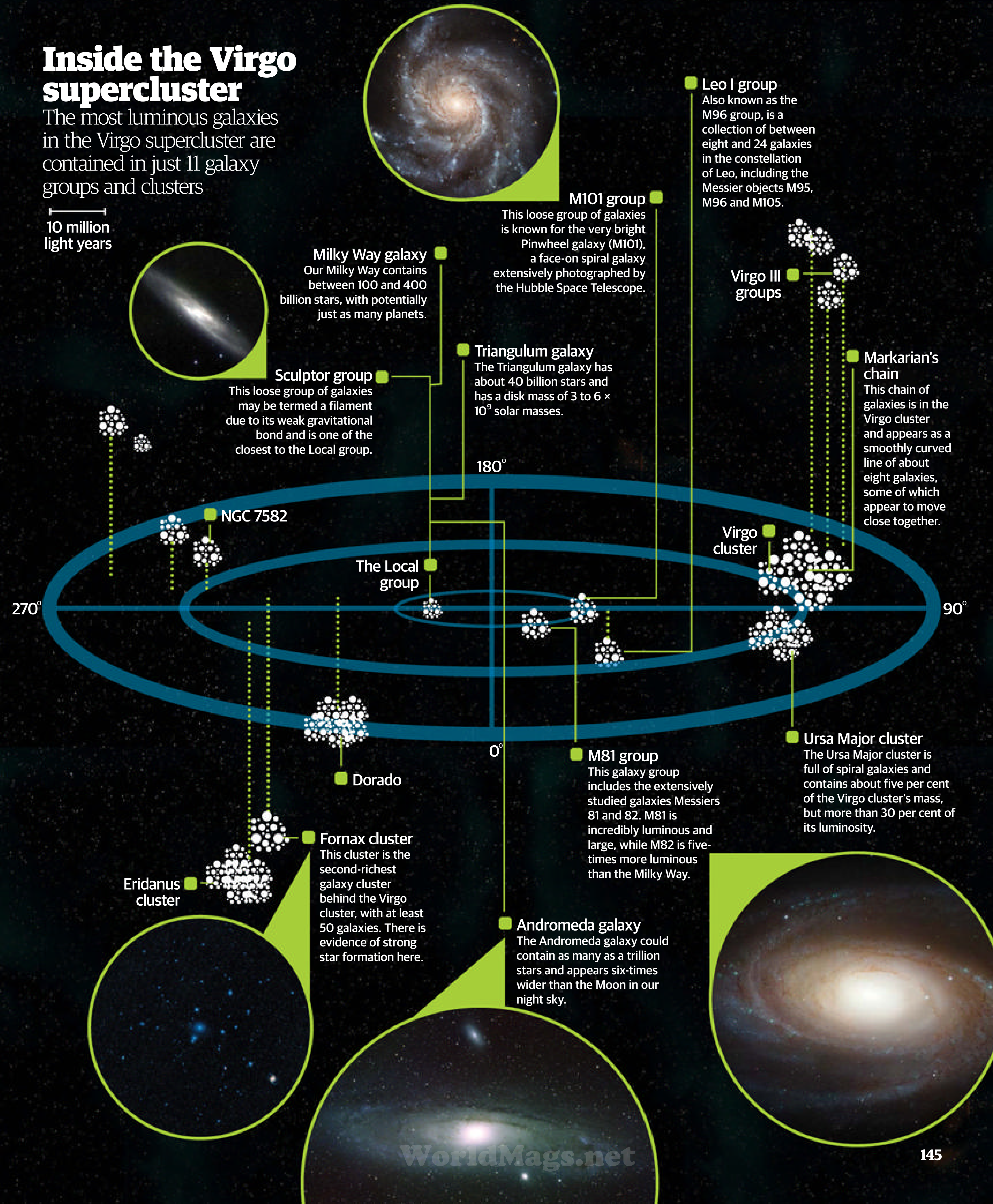
Some galaxies in the Local group are set to collide with others, or have collided in the past. Collisions are common in galaxy groups because of gravitational attraction and often result in the formation of larger galaxies, or at the very least alterations of their structures or orbits.

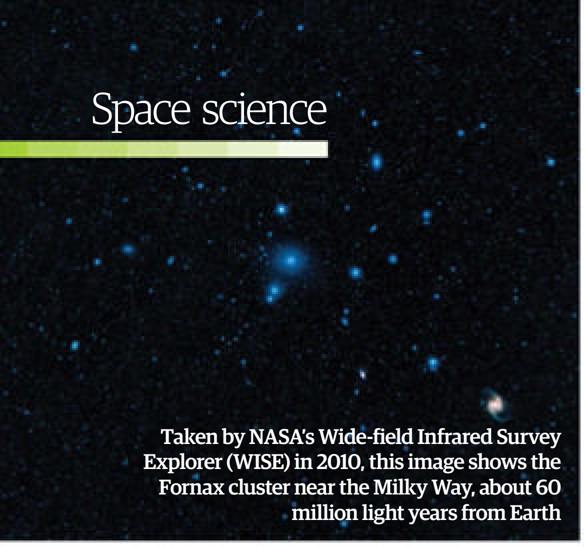
For example, the Sagittarius Dwarf Spherioidal galaxy will probably collide with the Milky Way if it maintains its current course, but some astronomers believe that such a collision has happened before and could be at least partially responsible for the spiral arm structure of our native galaxy.

Collisions between two smaller galaxies have also resulted in larger ones being produced – the Andromeda galaxy probably formed this way. The Milky Way and Andromeda may themselves collide in about four billion years. While it's unlikely that any stars will actually collide, the galaxies themselves merge to form a giant elliptical galaxy and the supermassive black holes at their centres converge.

Inside the Virgo supercluster

The most luminous galaxies in the Virgo supercluster are contained in just 11 galaxy groups and clusters





Taken by NASA's Wide-field Infrared Survey Explorer (WISE) in 2010, this image shows the Fornax cluster near the Milky Way, about 60 million light years from Earth

Located three million light years from Earth, the Triangulum galaxy image was taken by the instruments aboard the Swift spacecraft

Taken from Earth, this image shows the tiny dwarf spheroidal galaxy Leo I as a faint patch to the right of the bright star Regulus

Observing Virgo

The origins and future of exploring the supercluster

The Virgo supercluster has only been known by this name since the 1950s – and it's been a long journey from its initial observation to what we know today. Astronomer Charles Messier, author of the *Messier Astronomical Catalogue of Nebulae and Star Clusters*, noted that there were many nebulae near the edge of the Virgo constellation. At the time, the term 'nebula' (an interstellar cloud of dust and gas) was used to describe any kind of cloud-like astronomical object.

Pioneering astronomers John and William Herschel also observed the nebulae and published a study in 1864. Harlow Shapley and Adelaide Ames first used the term 'cluster', calling the galaxies they observed a 'cluster of bright spiral nebulae', in the late 1920s. Then Edwin Hubble and M.L. Humason classified some of the galaxies in the region as belonging to the Virgo cluster in 1931.

The VS began to be better understood in 1958, due to the work of astronomer Gérard Henri de Vaucouleurs. He argued that these galaxy clusters are grouped into even larger clusters – superclusters – due to gravitational attraction. He first called the Virgo supercluster the Local supergalaxy and later the Local supercluster, the latter of which is still used as a name for it. Initially Vaucouleurs' theories were controversial and astronomers continued to debate about whether the supercluster could be an organised structure, or if the proximity was just coincidental.

"The VS is a somewhat flat, gravitationally bound structure"

The debate all but ended with redshift surveys conducted in the 1970s and 1980s, the first of which was the CfA Redshift Surveys that began in 1977. These surveys measured the redshift of an astronomical object to create a 3D map of a particular section of sky. The data could be used to determine the distance of galaxies and make measurements of the largest objects in the observable universe. A galaxy's redshift (or blueshift, if it's moving towards us) is the way that its spectral features shift to longer (or shorter) wavelengths.

Both the expansion of the universe (the Hubble Flow) and Doppler motions trigger these changes in the wavelengths caused by the motion of the object itself. Ultimately these surveys proved that the Virgo supercluster is a flat, gravitationally bound structure consisting of galaxy groups and clusters. They also showed that the universe has a honeycomb-like structure of filaments, sheets and walls of galaxies.

Many of the most powerful telescopes in the world, including the Large Binocular Telescope (right), have spent time studying the features of the VS. But it's impossible to discuss observations of this supercluster without mentioning the Hubble Space Telescope (HST). Launched in 1990, the HST has given us some of the most iconic images of different galaxies in the VS. This includes the largest and most detailed HD portrait of a spiral galaxy – a stunning image of the Pinwheel galaxy (M101). It has also shown us new galaxies and determined their place in the supercluster. For example, studies of HST observations have shown that the Large Magellanic Cloud and Small Magellanic Cloud, believed to be orbiting the Milky Way, might be moving too fast to be more than just passing through.

On land, the Keck Observatory's twin telescopes are among the most powerful in the world. Among its recent observations in the supercluster is both one of the smallest and the most significant. In June 2013, it revealed more information about one of the tiniest galaxies – Segue 2 located in the Milky Way. With just 1,000 stars and a small globule of dark matter, this very faint galaxy may reveal more about how galaxies form. This just goes to show that while the Virgo supercluster may be just one out of millions, it's still revealing vast amounts of information about our universe as a whole.

Captured by Swift, this image of the Andromeda galaxy 2.5 million light years away is the highest-resolution view of a spiral galaxy ever attained in ultraviolet

Large Binocular Telescope (LBT)

First observation
The first image from the LBT was NGC 891, an edge-on spiral galaxy in the NGC 1023 group located in the Canes Venatici cloud of the VS.

Star formation
The LBT's observations of the Trapezium region in Orion have revealed the positions of young stars in their orbits and confirmed a theory about the nature of star formation.

The LBT is a collaborative project between institutions based in the USA, Italy and Germany

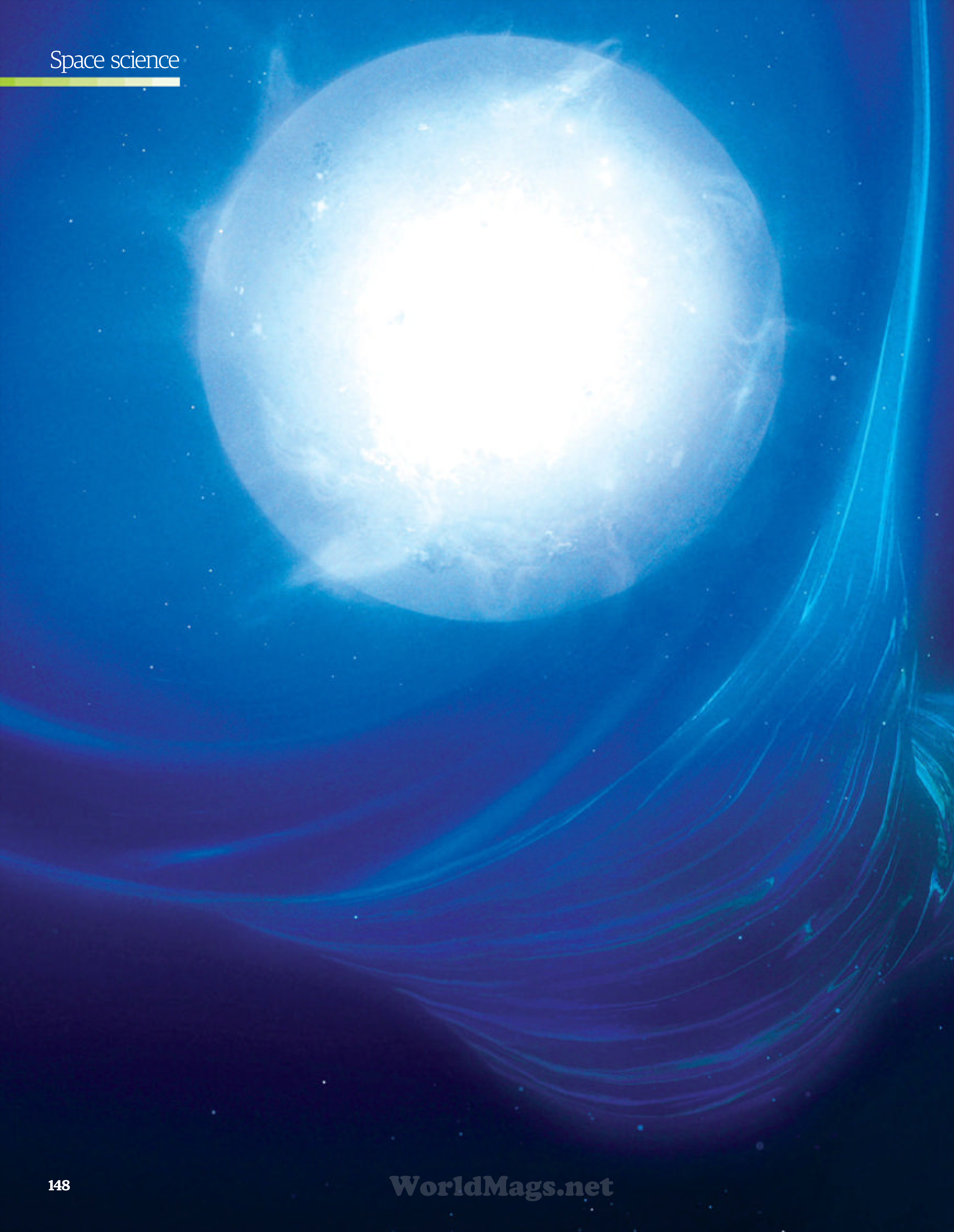
Mirrors
The LBT has two 8.4-metre- (27.6-foot-) wide mirrors that are separated in the centre by 14.4 metres (47.2 feet) and an adaptive mirror to correct distortion.

Prime focus camera
Looking at Messier 81 in the M81 Group using the UV-blue camera revealed the faint dwarf galaxy Holmberg IX.

Installation
The LBT saw first light with a single mirror in October 2005 and the second mirror was installed in 2006.

Partners
The LBT is a joint project of several universities and scientific organisations located in the United States, Italy and Germany.

Location
This telescope is located at Mount Graham International Observatory, in the Pinaleño Mountains of Arizona, USA.



The search for wormholes

We speak to the teams of scientists searching for wormholes in an attempt to uncover the facts behind the science fiction

Wormholes are so-called gateways that provide a shortcut through the fabric of space-time. They can be thought of as tunnels with ends capped by an ever-hungry black and a white hole, the black hole's time-reversed cousin that prefers to spit things out if anything comes too close to its event horizon.

It's true that a wormhole never looks out of place in science fiction, for example lurking in the universe of *Deep Space 9* and employed by captain Benjamin Sisko and his crew of the Defiant. They use the hole to travel from the Alpha to the Gamma quadrant on the other side of the galaxy at unprecedented speed – certainly a thrilling prospect.

However, we still don't know for sure whether traversable wormholes like the ones in *Star Trek* really exist. Even finding the slightest hint of these natural portals almost seems like a pipe dream. With this in mind, it would seem odd that massive organisations are still looking, such as Project RadioAstron, the Soviet Union's first radio astronomy research facility.

"The search for wormholes seems like a worthy undertaking," muses assistant professor of astrophysics Robert Owen of Oberlin College. His thoughts are echoed by Igor Novikov, a Russian theoretical astrophysicist and cosmologist who made

Interview

Why are we looking for wormholes?

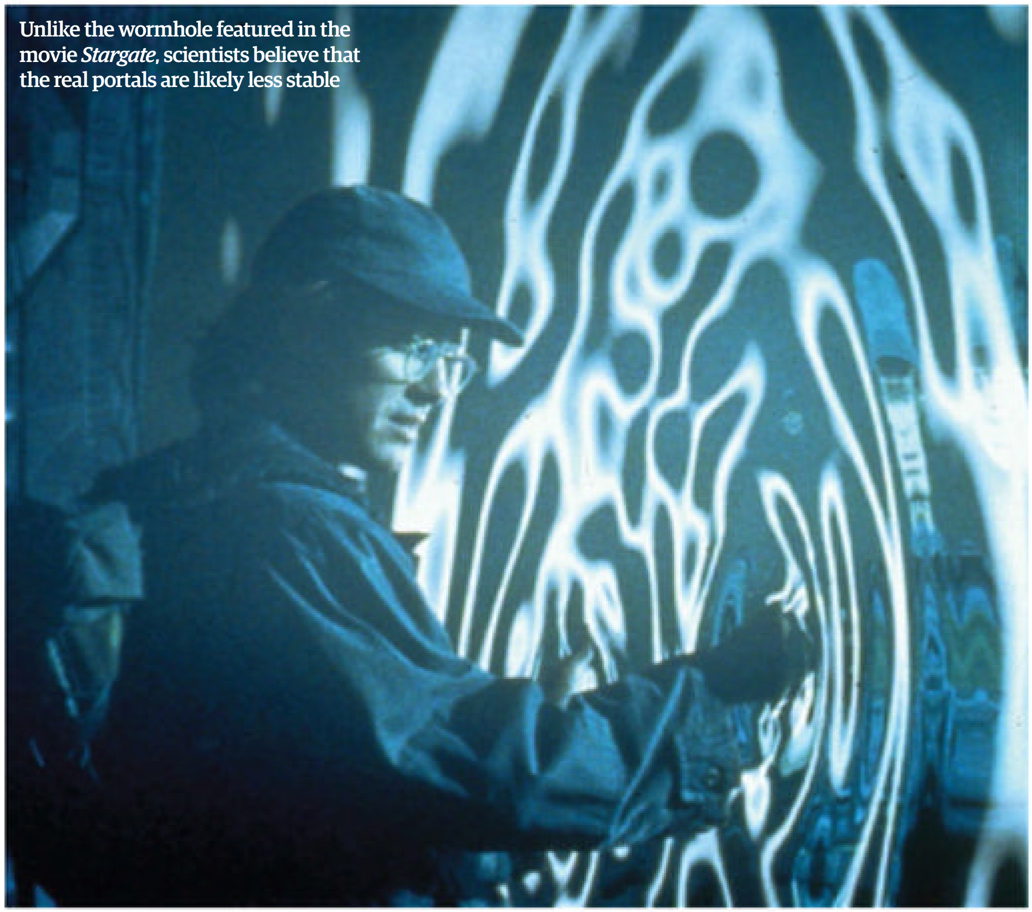
Professor Robert Owen, of Oberlin College, USA, tells us why hunting for wormholes is so necessary

"I think it's extremely important that we continue to search for and research the ideas behind wormholes. There are all sorts of [avenues for] research and we often find that some subjects are more practical than others. Obviously wormhole physics is not a very practical subject but wormholes and other exotic phenomena, provide a route to understanding some of the deepest questions about the nature of our universe - the arena of our very existence. For that reason alone, this is an exciting endeavour and deserving of support for its own sake.

"It's also important to note subjects that might seem highly impractical could eventually be central to our daily lives. Electromagnetic theory was at one time considered an impractical subject and now it's fundamental to everyday life. Quantum theory has long been viewed as an arcane body of research, but now it's essential for the inner workings of much modern technology.

"Another important point is that all research is fundamentally interconnected with insights made in one field of study often transferred into others. For example, there is a long-standing symbiosis between research in particle physics and solid-state physics - the field that provides much of our understanding of the properties of materials. There is a constant conversation between these two fields of study and ideas are regularly shared between them. In a broader sense, this occurs throughout the sciences. So there's really no way of knowing ahead of time what the eventual significance of any field of research might be.

"Einstein's general theory of relativity predicts quite clearly that if a wormhole existed, it would be unstable and we wouldn't be able to use it for practically travelling through time. However, with all scientific questions, we can't be completely certain that general relativity, in the form that we currently understand it, is the most accurate possible description of space-time in all situations. It could be that in certain situations general relativity becomes inaccurate, just as Newtonian physics becomes inaccurate near a black hole, for example. This means I certainly wouldn't rule out the idea absolutely, until we have some good astronomical evidence."



Unlike the wormhole featured in the movie *Stargate*, scientists believe that the real portals are likely less stable

an important contribution to the theory of time travel during the mid-1980s. The Novikov Self-consistency Principle states that it's impossible to make paradoxes of time. "There's a hypothesis that primordial wormholes exist and can connect some regions in our universe in the model of the multiverse," Novikov, who is based at the Russian Space Research Institute in Moscow, explains. "In this case, the search for astrophysical wormholes is a unique possibility to study the other universes."

These elusive tunnels through space wouldn't just be a major discovery in and of themselves, but could even open up avenues to bigger things - possibly even answering some of the deepest questions about the nature of our universe. Although we haven't found them yet, the laws and complex equations that underpin Einstein's theory of general relativity say that, technically, they should exist out there somewhere - maybe as microscopic structures the size of atoms, or giant but impassable wormholes connecting the black holes in the centres of galaxies. However, should a stable wormhole be found, it might be possible to travel down it and end up in another place, and another time, in the universe.

Clearly the practicalities of finding a wormhole is a challenging subject entirely on its own and one that scientists like Owen relish. The search wouldn't merely mean searching for the wormholes themselves, but the equally elusive white holes that are supposedly tacked onto one end, making the task of locating them all the more difficult. However, despite this, Owen believes that despite the obvious difficulties, the hunt for wormholes must be supported. He studies the relativistic effects of black holes and neutron stars colliding to make gravitational waves - ripples in the curvature of space-time - to find traces of the holes.

So, is finding a wormhole really that important at all? We asked theoretical physicist Kristan Jensen at the University of Victoria. Alongside Andreas Karch, a professor of physics at the University of Washington, Jensen looks at wormholes purely from a theoretical perspective. "Honestly, no," he initially answers. "I find it unlikely that there are wormholes [of notable size] in our universe." This is because he - as well as quite a few in the scientific community - believe that we might be hard-pressed to find these tunnels through space. Paradoxically, it seems that the theory suggesting that wormholes exist also makes an equally strong case for how they could never be real.

If you were to open up a wormhole, you might find it quickly begins to fall apart. Egyptologist and linguist Daniel Jackson, the protagonist in *Stargate*, might have found himself cautiously stepping into a

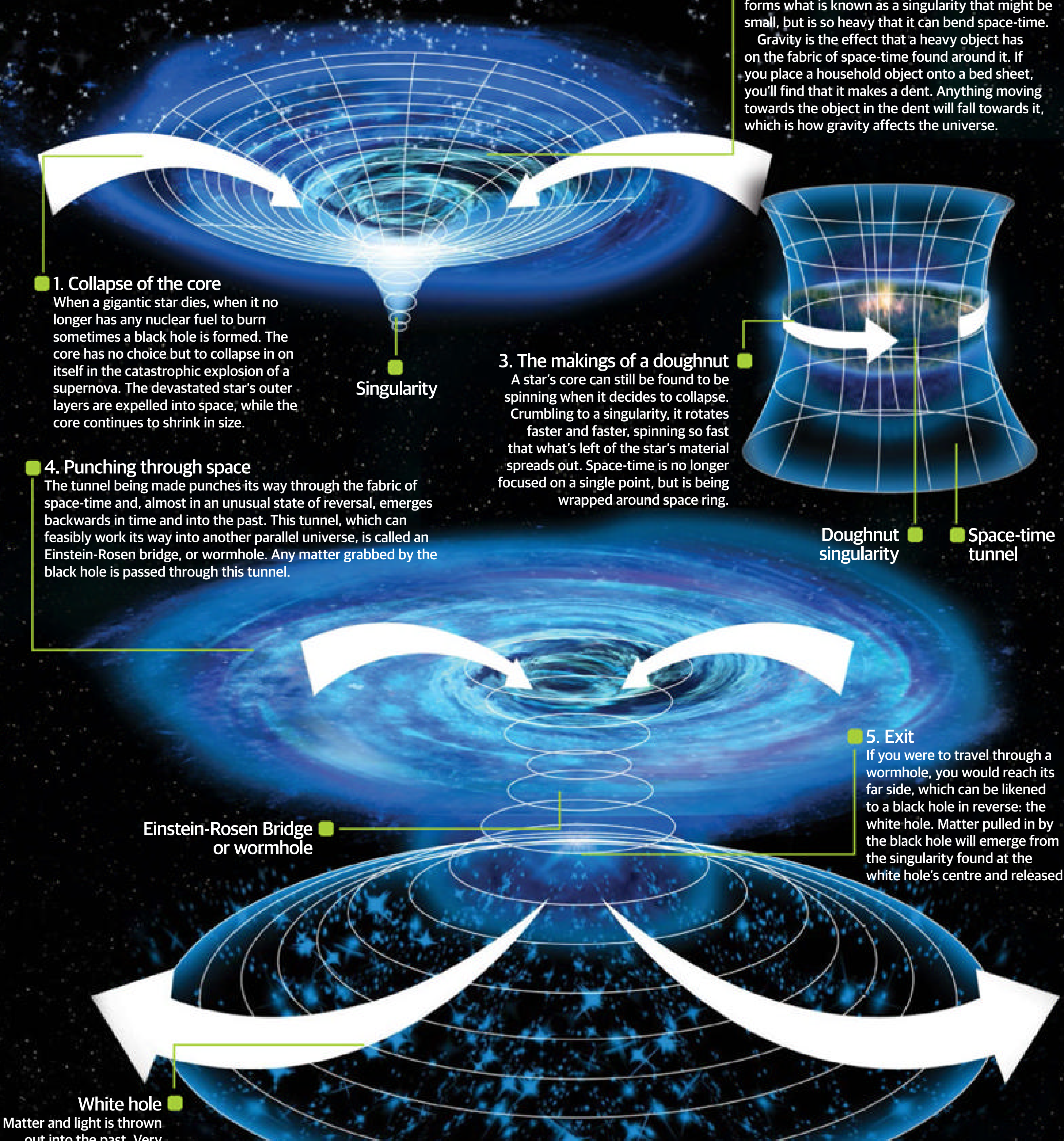
"In general relativity, time travel is actually one of the things that naturally comes along with wormholes" **Prof Robert Owen**

The making of a wormhole

Black hole
Everything – from matter to light – is pulled into a high-gravity black hole. Quite confusingly, this is the future end of the wormhole.

2. A cosmic plug hole
Shrinking smaller and smaller, the core continues to pale in significance compared with its former stellar glory. While it has shrunk to a speck, all of its mass is concentrated in a very small area. This forms what is known as a singularity that might be small, but is so heavy that it can bend space-time.

Gravity is the effect that a heavy object has on the fabric of space-time found around it. If you place a household object onto a bed sheet, you'll find that it makes a dent. Anything moving towards the object in the dent will fall towards it, which is how gravity affects the universe.



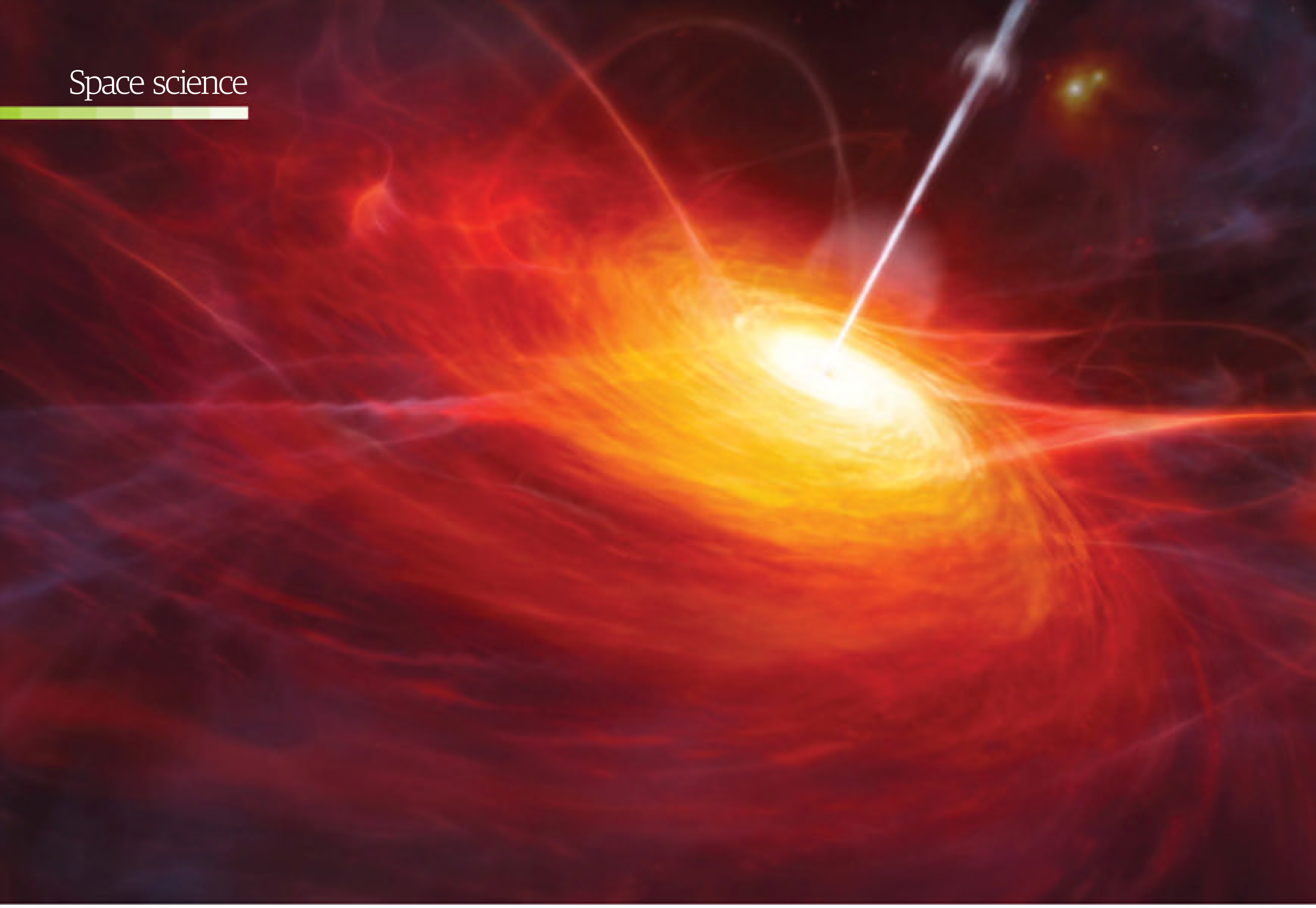
1. Collapse of the core
When a gigantic star dies, when it no longer has any nuclear fuel to burn sometimes a black hole is formed. The core has no choice but to collapse in on itself in the catastrophic explosion of a supernova. The devastated star's outer layers are expelled into space, while the core continues to shrink in size.

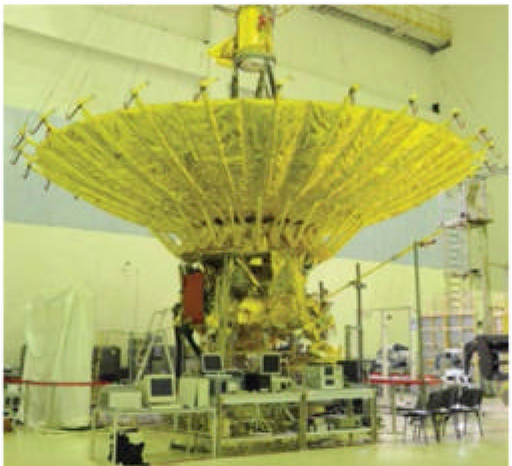
3. The makings of a doughnut
A star's core can still be found to be spinning when it decides to collapse. Crumbling to a singularity, it rotates faster and faster, spinning so fast that what's left of the star's material spreads out. Space-time is no longer focused on a single point, but is being wrapped around space ring.

4. Punching through space
The tunnel being made punches its way through the fabric of space-time and, almost in an unusual state of reversal, emerges backwards in time and into the past. This tunnel, which can feasibly work its way into another parallel universe, is called an Einstein-Rosen bridge, or wormhole. Any matter grabbed by the black hole is passed through this tunnel.

5. Exit
If you were to travel through a wormhole, you would reach its far side, which can be likened to a black hole in reverse: the white hole. Matter pulled in by the black hole will emerge from the singularity found at the white hole's centre and released.

White hole
Matter and light is thrown out into the past. Very much like a smaller version of the Big Bang.





Space radio telescope Spektr-R launched in 2011, is part of Russian venture Project RadioAstron

The telescope took its first readings on 27 September 2011, capturing the ancient star Cassiopeia A

"All you need to enter a wormhole is a spacecraft. Just dive in and go" **Dr. Eric Davis**

stable wormhole when he cracked the code behind the hieroglyphics that opened a pathway to another galaxy. The reason that we might not be able to find a wormhole could simply be that in reality they're incredibly unstable entities.

Owen suggests that you just need to think about travelling through one to get a full picture of why this is. "In general relativity, time travel is actually one of the things that naturally comes along with wormholes," he says. "However, the idea that wormholes could be used for travelling through time is usually taken as an indication that they probably couldn't exist." Owen references several calculations that have been processed, showing that wormholes naturally destroy themselves before they could even offer us the chance to be used to travel back in time.

"Imagine that I had a wormhole with both throats [in other words, both openings to the wormhole], in my office and I could step into one of them and emerge from the other ten seconds earlier," he describes. "For those ten seconds there would actually be two of me in the office. But what if I then chose to wait those ten seconds and then step through [the black hole again], simultaneously with my earlier self?" The answer is that Owen and his past self would again emerge from the white hole ten seconds earlier and there would now be three of him in the office. "If I did it again, there would be four of me, five, six and so on," he continues. "This silly story illuminates the way that a wormhole would naturally destroy itself."

Owen is talking about feedback, just like the feedback you might get on a microphone, because it's not just people that could take a trip though these time-tunnelling wormholes. Radiation, be it light or heat, can also enter the wormhole and do exactly the same thing as the multiple Robert Owens. So much energy would end up in the loop that it would cause the wormhole to collapse.

Another problem is that a wormhole would be too small for a single person – let alone a spaceship capable of interstellar travel – to be able to comfortably fit through. To successfully pass through a hole, we would need to find some way of enlarging one, something that seems unfeasible given that we don't even yet have proof of its existence.

However, not everyone thinks that the journey would be entirely impossible. One of the world's leading theoretical physicists, Kip Thorne, is professor

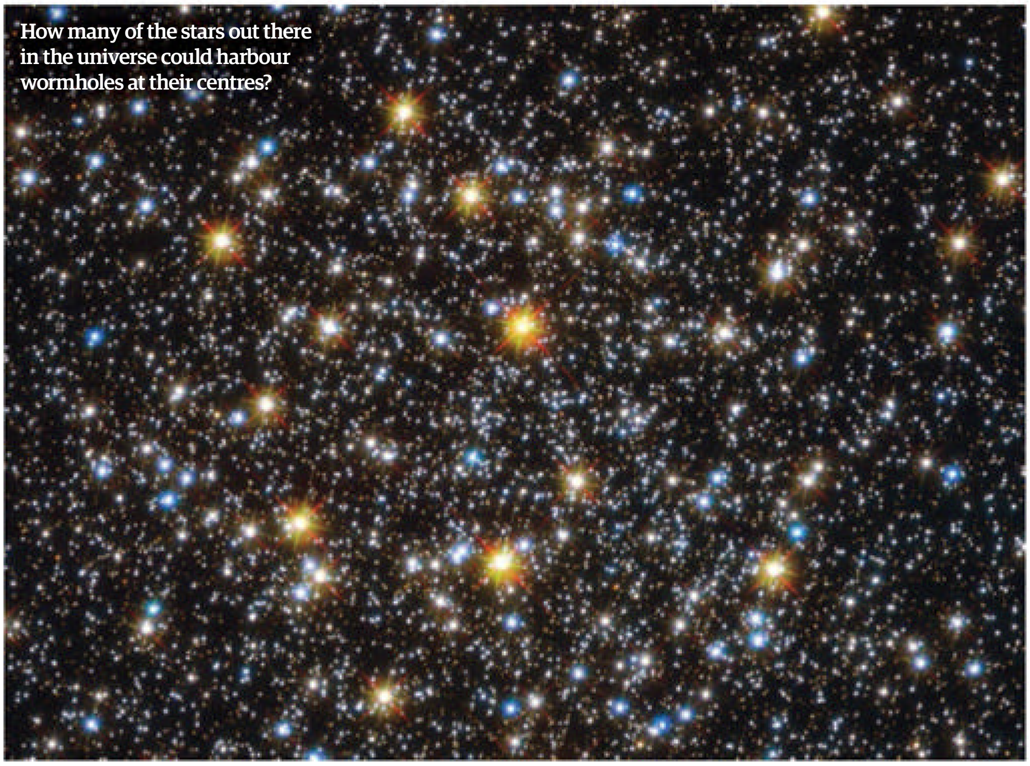

Scientists behind Project RadioAstron suspect a wormhole is at the centre of quasar 3C273, due to its increase in temperature and odd magnetic field

emeritus at the California Institute of Technology (Caltech) and a long-time friend of both Stephen Hawking and the late Carl Sagan. Thorne not only thinks that these portals might exist somewhere out there, but that they could also be used as some kind of time machine, capable of getting us from one place in the universe to another.

Another scientist who has confidence in the possibility of using wormholes for travel is Eric Davis, a senior research physicist at the Institute for Advanced Studies at Austin, Texas. "All you need to enter a wormhole is a spacecraft. Just dive in and go," he says. "If the wormhole is too small for a spacecraft, then it has been posited by Kip Thorne, the man who discovered suggestions of traversable wormholes in Einstein's theory of general relativity, that all one may need to do is feed the wormhole more negative energy density and/or more-negative pressure to inflate it up to a larger size."

So, what is negative energy? Dark energy, which is causing the universe to expand, is an example of a negative energy pressure - something that is opposing forces such as gravity. However, we don't even know what dark energy is, let alone any way to create true negative energy, suggesting that we won't be venturing down a wormhole any time soon.

Still, this isn't to say that nature hasn't found a way to enlarge wormholes, which is exactly what Russian scientists working on Project RadioAstron are banking on. They are using the largest space telescope ever launched - not Hubble or the Herschel Space Observatory, but Spektr-R, a radio telescope


How many of the stars out there in the universe could harbour wormholes at their centres?

Debate

Are wormholes likely to exist?

Two experts give their opinions on whether or not we'll ever find these tunnels piercing through space-time

Yes


Dr Eric Davis, senior research physicist at the Institute for Advanced Studies

"Yes, wormholes should exist in nature, because they are predicted by Einstein's theory of general relativity, which is the theory that also predicted black holes, cosmology, neutron stars, the gravitational lensing of galaxies, gravitational redshift and time dilation, the bending of light by stars (gravitational lensing) among other things.

"All of these astrophysical phenomena have been repeatedly observed to high precision and so verify the general relativity theory. There is no reason why wormholes shouldn't exist based on a very well-tested theory whose other predictions have been verified as previously mentioned. Another prediction of general relativity is the existence of gravitational waves [which could form an indication of the existence of wormholes], and there has been a search for their existence going on for over 50 years. This search is now ramping up with a major British astronomy program dedicated entirely to detecting them."

No


Professor Andreas Karch, a professor of physics at the University of Washington

"No, I would completely agree that most likely they are just a theoretical construct. It's very unlikely that we will ever see the more-standard kind of wormhole - the one that you could traverse through, as seen in science-fiction movies.

"According to our understanding of physics, these traversable wormholes seem almost impossible and we certainly haven't seen one. Even if they exist, I'm not sure how to hunt for them. One couldn't measure the existence of a wormhole directly without sending in two observers into the two connected black holes [which could also form the basis of a wormhole]. If they meet in the middle, there's a wormhole. If not, then there's no wormhole. In any event, the more-fortunate external observers would never know the outcome of the experiment.

"Of course, that doesn't mean that one should stop looking - we should always look for what's out there, however, I wouldn't hold my breath."

The story of the wormhole

Building bridges

In 1935 Albert Einstein and Nathan Rosen were the first scientists to come up with the idea of wormholes. They described how their theory presents a description of space by means of two sheet, while a spatially finite bridge connects these sheets. Technically they are known as Einstein-Rosen Bridges, but the American physicist John Wheeler introduced the term wormholes for them in 1957.

Clocks run slower

Kip Thorne theorised that wormholes can act as time machines. Imagine you have a wormhole and you take one mouth of it and accelerate it close to the speed of light, before bringing it back. According to special relativity, time runs slower for things moving near the speed of light, so a clock inside the accelerated mouth would show an entirely different time from the static end of the hole.

The Mad Scientist Paradox

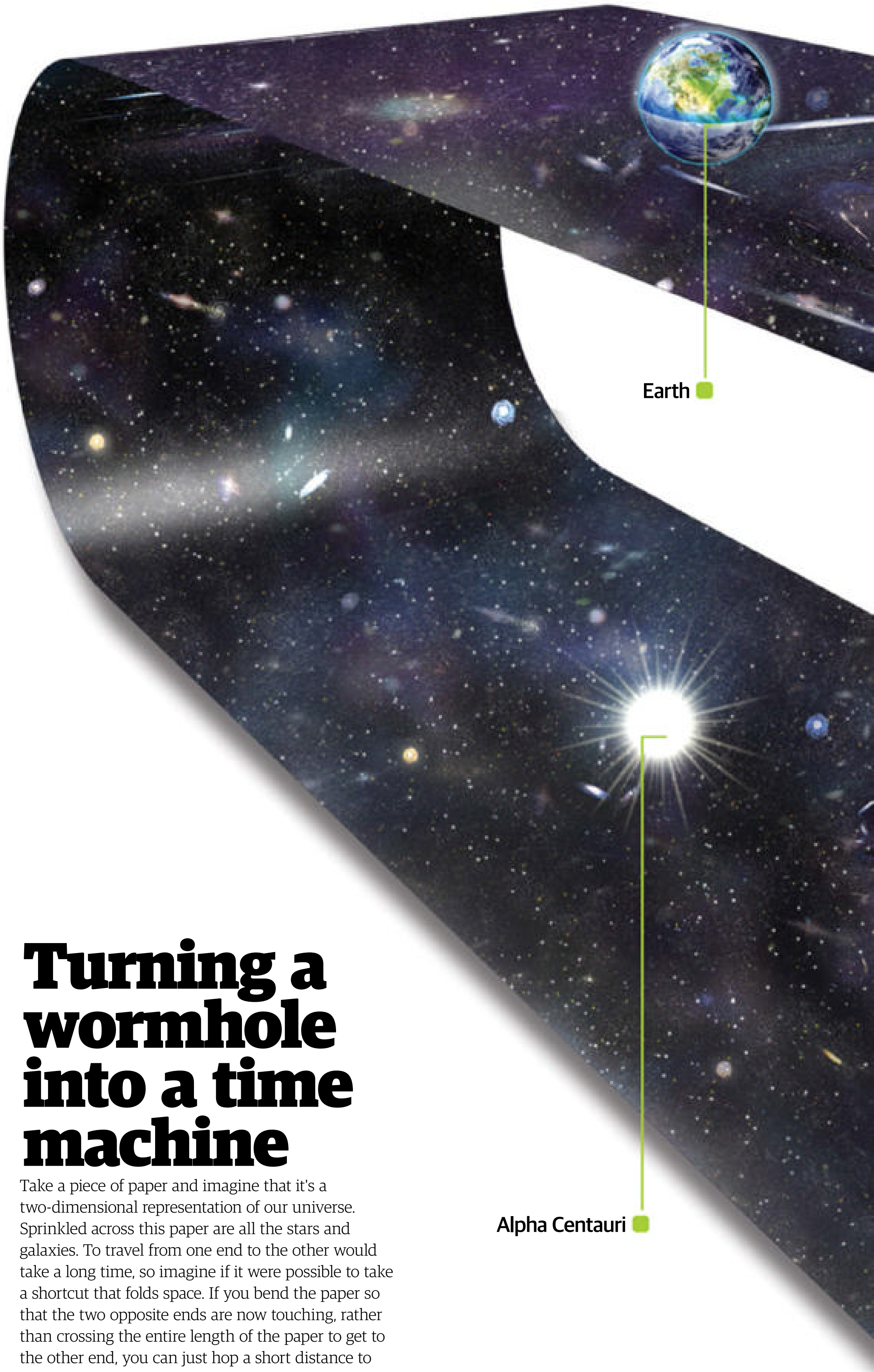
Stephen Hawking doesn't think it's possible to travel through a wormhole, even after capturing and enlarging one. He's concerned about time-travel paradoxes and uses the Mad Scientist Paradox as an example. Here a scientist creates a wormhole in his lab that takes him back ten minutes in time. Seeing himself ten minutes ago he shoots himself dead. Yet if he's dead in the past, how can he be alive in the future to shoot himself?

Uncertainty

Stephen Hsu and Roman Buniy of the University of Oregon suggested the uncertainty principle of quantum mechanics, stating that the more precisely a property of a particle is known, the less precisely other properties can be known. As wormholes involve quantum effects, Hsu and Buniy claim you can never know exactly where you will end up once you travel through the wormhole.

Interstellar

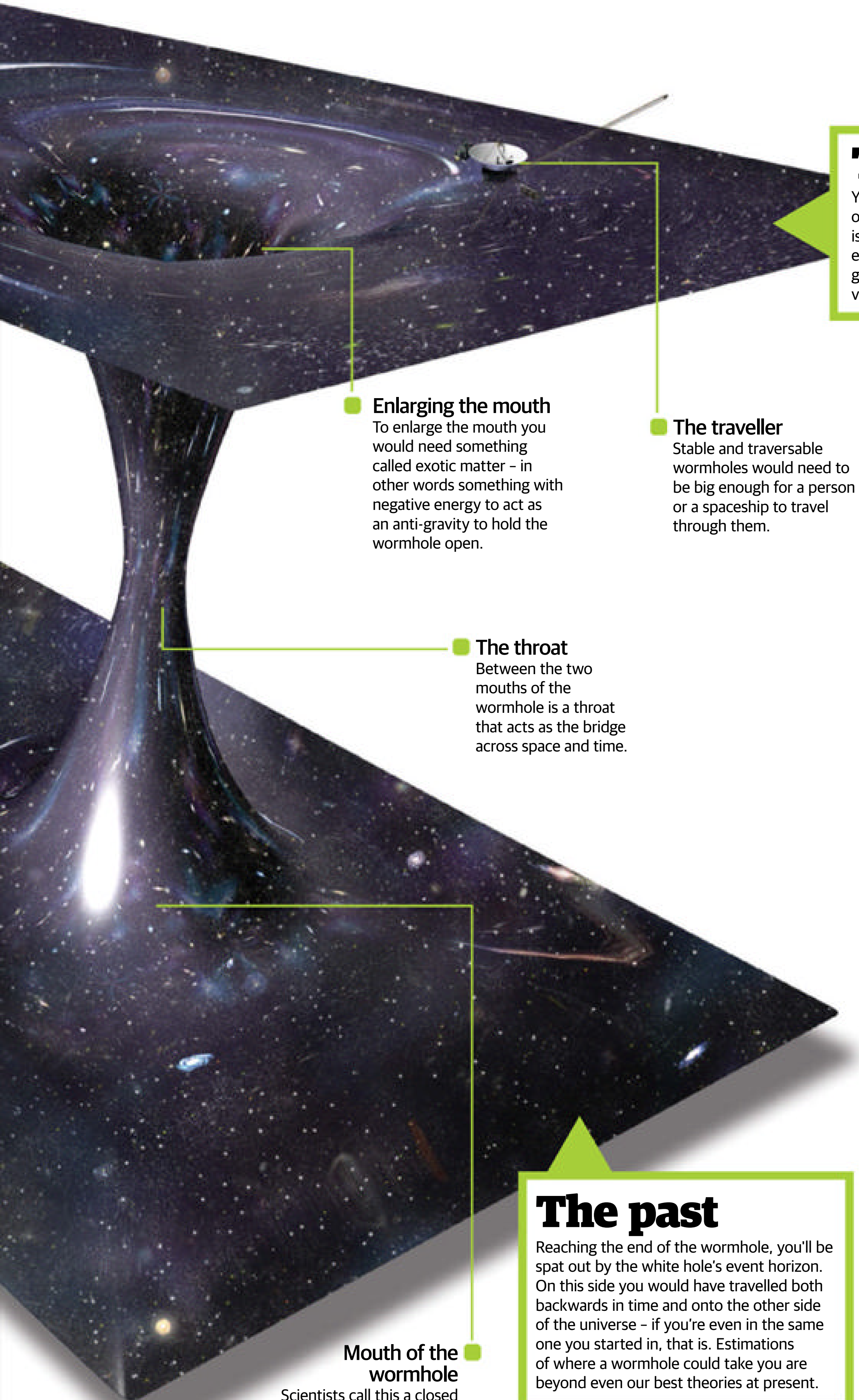
Kip Thorne's theories feature in this successful Hollywood blockbuster that he co-produced called *Interstellar*, which involved travel through a wormhole and was released in November last year. Thorne himself is no stranger to science fiction – when Carl Sagan needed a means of faster-than-light space travel for his novel *Contact*, Thorne developed the science behind wormholes that Sagan could then use in his story.



Turning a wormhole into a time machine

Take a piece of paper and imagine that it's a two-dimensional representation of our universe. Sprinkled across this paper are all the stars and galaxies. To travel from one end to the other would take a long time, so imagine if it were possible to take a shortcut that folds space. If you bend the paper so that the two opposite ends are now touching, rather than crossing the entire length of the paper to get to the other end, you can just hop a short distance to reach it. The idea is that a wormhole would act like a bridge to connect the two ends together.

Now imagine that the paper doesn't just represent space, but also time. This means that a wormhole doesn't just connect two different spaces within the universe, but can also connect two time periods. This accompanying diagram illustrates exactly how this could be possible.



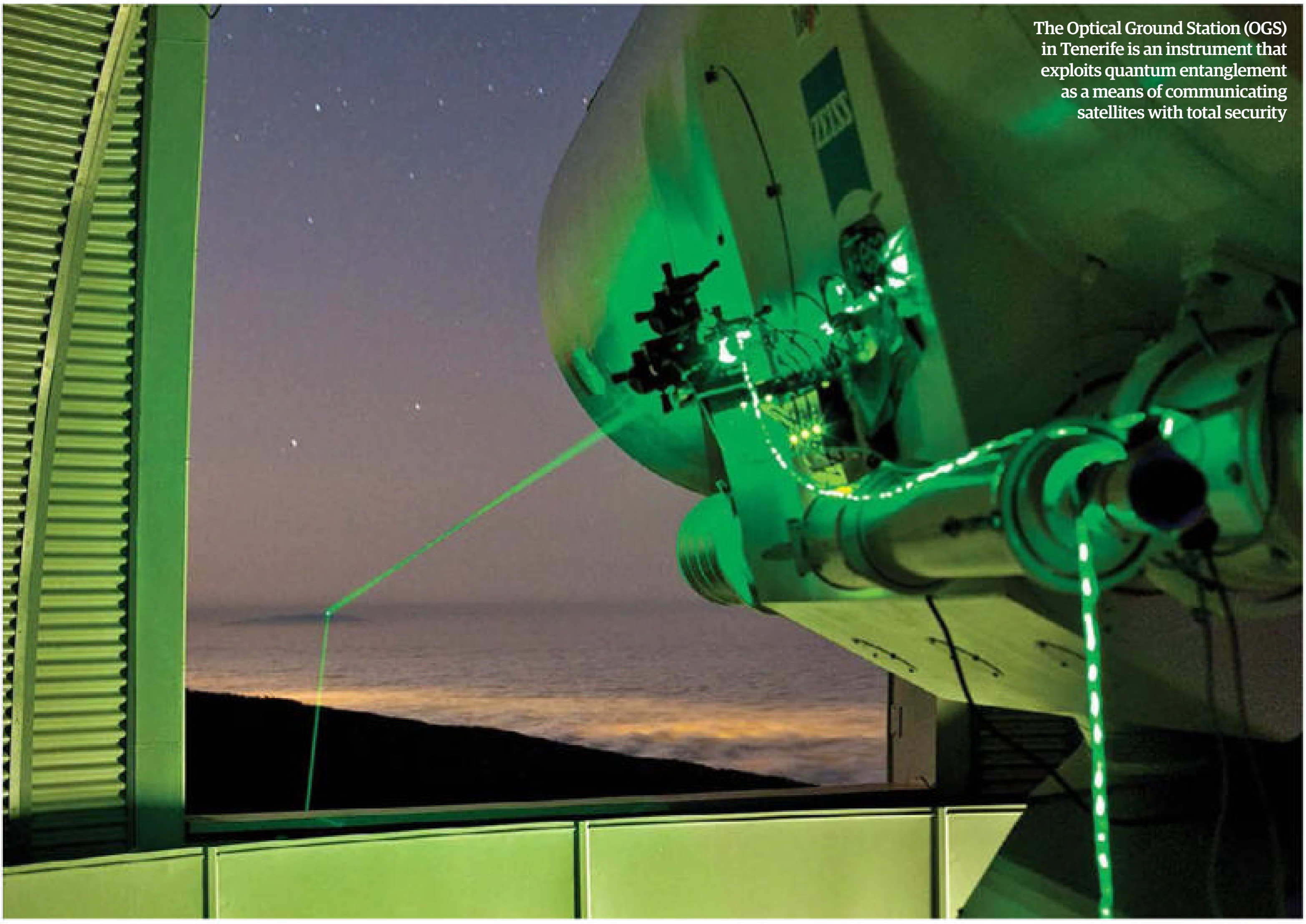
that launched into space in 2011 and has a detector diameter of ten metres (33 feet). The hope is that with Spektr-R they will finally discover evidence for wormholes and white holes.

The project's initial steps into probing the universe were originally quite bleak, because the Soviet Union collapsed just as it was within reach of being completed, but now it has been restarted. Until quite recently an old radio telescope built in 1959, dubbed RT-22, was the main receiver of signals from the Spektr-R. For many months the receiver has been studying supermassive black holes found at the centres of galaxies and even probing the Milky Way's own black hole, Sagittarius A*. Observations of the black hole's event horizon - the point of no return from this exotic high-gravity beast - is where RadioAstron's aims get interesting.

Getting close to black holes could lead us to the elusive wormholes and white holes, according to RadioAstron scientists. The trick is to keep our eyes peeled for a certain signature. "We must look for the structure of magnetic fields near the centres of galaxies," says Novikov, who back in 1964 also pointed out that general relativity allows for the existence of white holes. "If the structures of the magnetic fields appear to be magnetic monopoles, that are macroscopic in size, then this is a wormhole. [These magnetic phenomena have only one pole and are predicted to exist but so far, like wormholes, have proven elusive]."

It turns out that wormholes - specifically their white holes - will emit their own radiation, in contrast with black holes that don't emit radiation themselves, but rather intensive radiation from the surrounding gas that spews out in swirls.

> "We should always look out for what's out there, however, I wouldn't hold my breath"
>
> **Professor Andreas Karch, University of Washington**



The Optical Ground Station (OGS) in Tenerife is an instrument that exploits quantum entanglement as a means of communicating satellites with total security

"There are many places that wormholes could be hiding, from inside black holes and stars, to the subatomic world"

We might not have detected a wormhole for sure, but it turns out RadioAstron might be on to something. Turning its attention to the core of quasar 3C273, in the constellation Virgo around 2.5 billion light years away, it has found something unexpected. Quasars are active galactic nuclei producing enormous amounts of radiation from around their black holes. We know there's a black hole in the heart of 3C273, but RadioAstron's observations show that it has increased in temperature. There's also the weird and wacky magnetic field that Novikov mentioned earlier, so RadioAstron must keep looking to verify the increasing suspicions of theoretical physicists.

Meanwhile, instead of using telescopes to scan the skies for these elusive tunnels, other astrophysicists have taken to imagining wormholes. For example, take the work of theoretical physicists Jensen and Karch, who have suggested that the particles of a quantum phenomena called entanglement are connected by miniature wormholes. When two particles interact they can become entangled so that their characteristics correlate. The famous Heisenberg Uncertainty Principle means that the quantum states, or properties of the particles such as their spin, remain undefined until they're measured properly. However, when the spin of one of the entangled particles is measured, then the other particle instantly follows suit, even if each of them are on opposite sides of the universe at the time.

How they communicate across huge distances so quickly is not truly understood, but Karch and Jenson have proposed that tiny black holes that have become entangled may have wormholes connecting them. Julian Sonner, of the Massachusetts Institute of Technology, has taken this idea a step further, showing that wormholes could connect entangled quarks, which are the fundamental particles that make up protons and neutrons inside of atoms.

Another place where theorists are looking for wormholes is inside stars themselves, although their location might make it a little bit difficult for us to reach them. Vladimir Folomeev of the Institute of Physicotechnical Problems and Material Science in the Kyrgyz Republic (Kyrgyzstan) has suggested that if exotic phantom matter exists – the same kind of stuff as dark energy, which has negative energy density – then it's possible it could exist within stars.

"The idea is very simple," explains Folomeev. "If dark energy amounts to about 70 per cent of the total energy density of the universe, then it is natural to assume that in some cases mixed objects consisting of both ordinary matter and dark energy can exist." A mixed star would act oddly, affecting the star's mass and causing unusual oscillations as the negative energy phantom matter moves around inside the star.

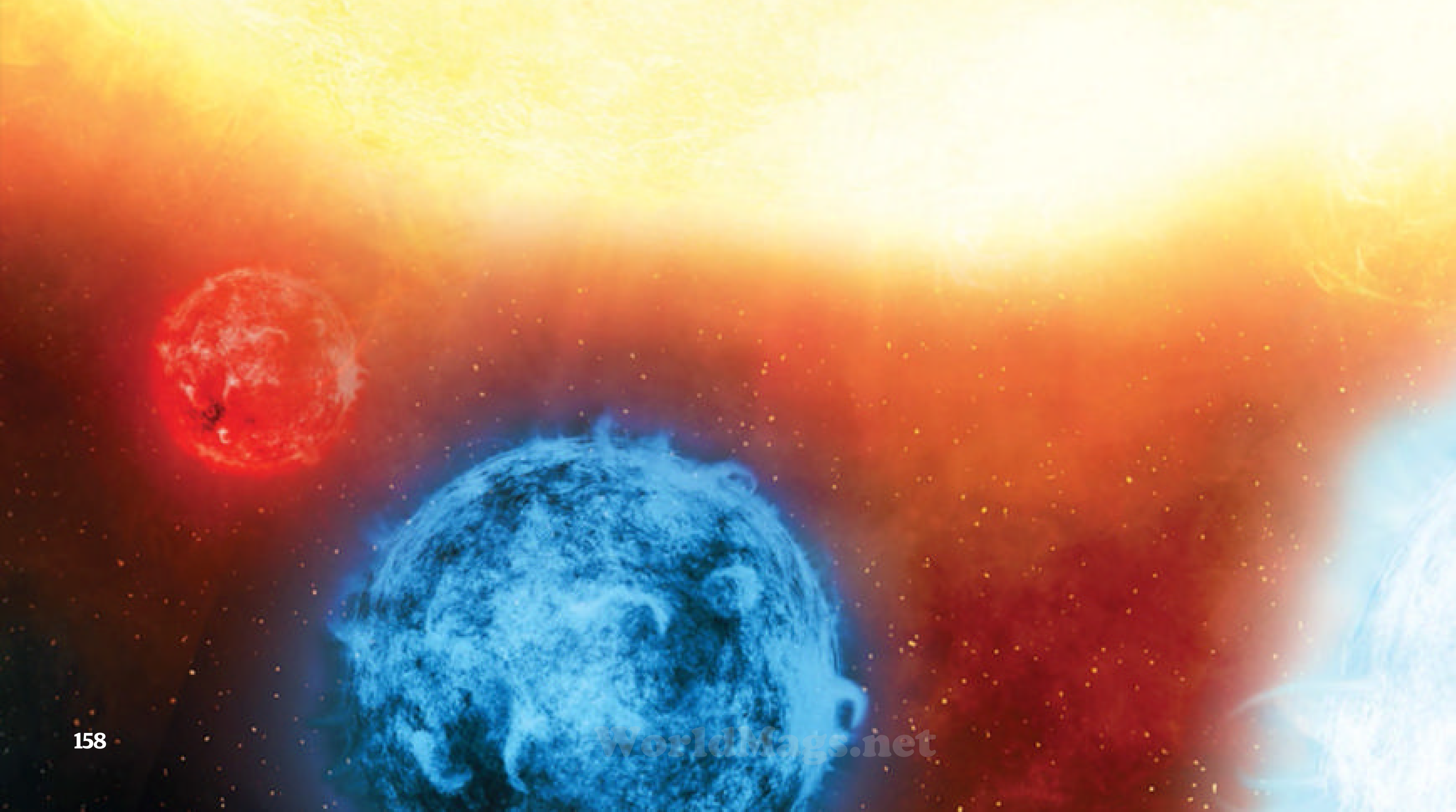
There are many places that wormholes could be hiding, from inside black holes and stars, to the subatomic world, but the big question is, what would it be like to travel down one? According to Davis, the mouth would look like a sphere with a distorted mirror image of the region of space on the other side of the wormhole, as the negative energy density deflects light passing through. When you pass through, the journey would likely be instantaneous and looking back you'd see another sphere reflecting where you came from. Across the universe in a single step – wormholes would be a truly giant leap.

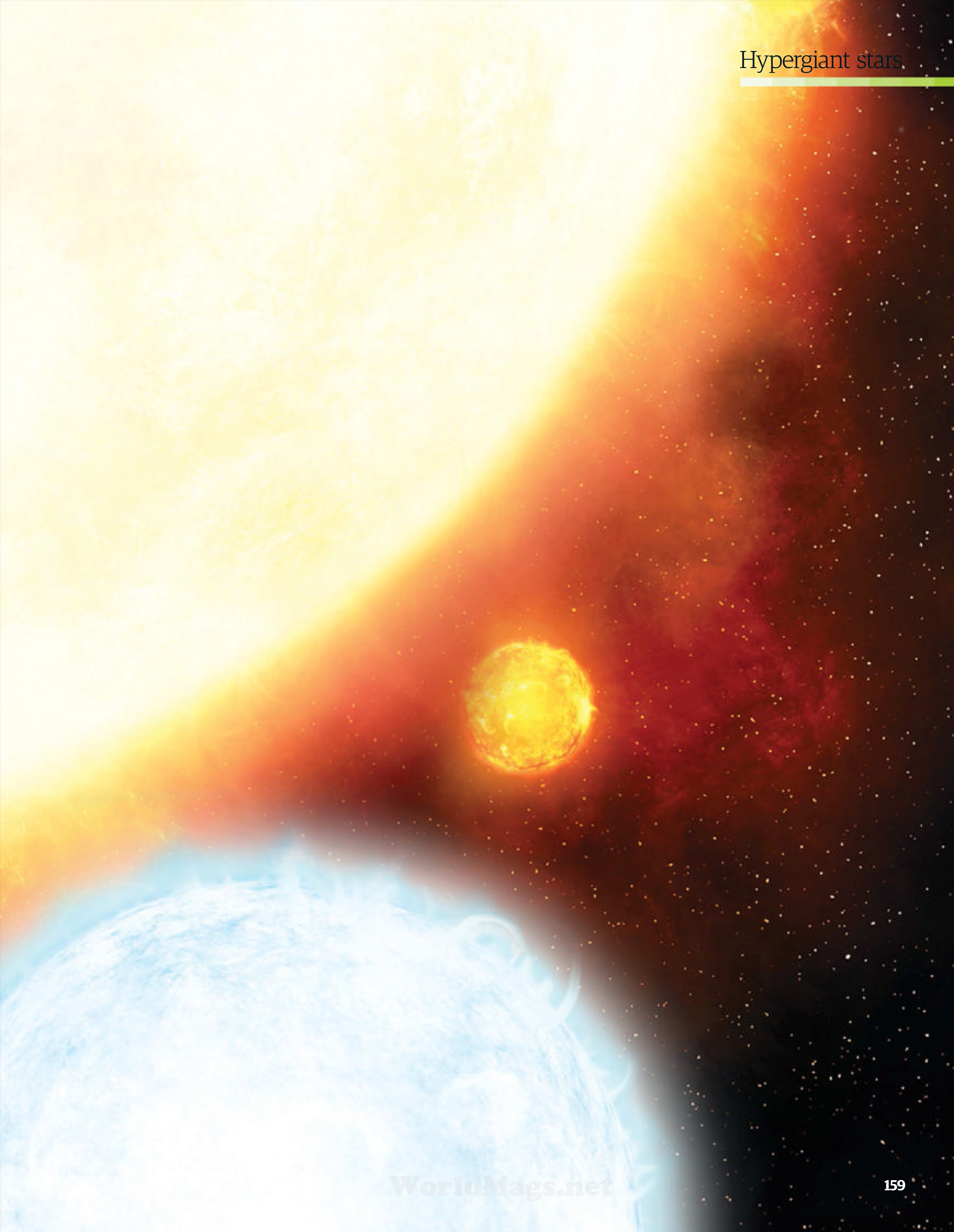
An artist's impression of quantum entanglement. If two photons of light are allowed to properly interact with each another, they can become entangled

"When you pass through, the journey would be instantaneous"

Hypergiant stars

They're the biggest stars in the universe – cosmic monsters up to a million times brighter than the Sun – so how do supergiant and hypergiant stars push the limits of astrophysics?





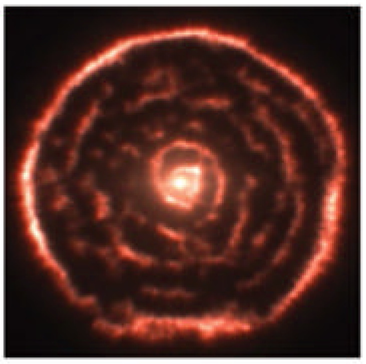
Look up at the sky on a dark night, and you'll see hundreds of stars. But only a few will really stand out – have you ever wondered why? For some, it's simply because they're quite close to Earth. For instance, Sirius is just 8.6 light years away – so, even though it's a fairly average star (though still 25 times more luminous than our Sun) it appears as the brightest star in our sky.

But other stars appear bright because they really are. The second brightest star in the sky, Canopus, is one such star – 310 light years from Earth and some 15,000 times more luminous than the Sun.

Stars in this class are usually known as supergiants – they have the mass of ten or more Suns, and evolve in a very different way from lower-mass 'Sun-like' stars, living fast, squandering their nuclear fuel and dying young in spectacular supernova explosions. The most massive stars of all, containing many tens or even hundreds of solar masses of material, are hypergiants, the most extreme stars known.

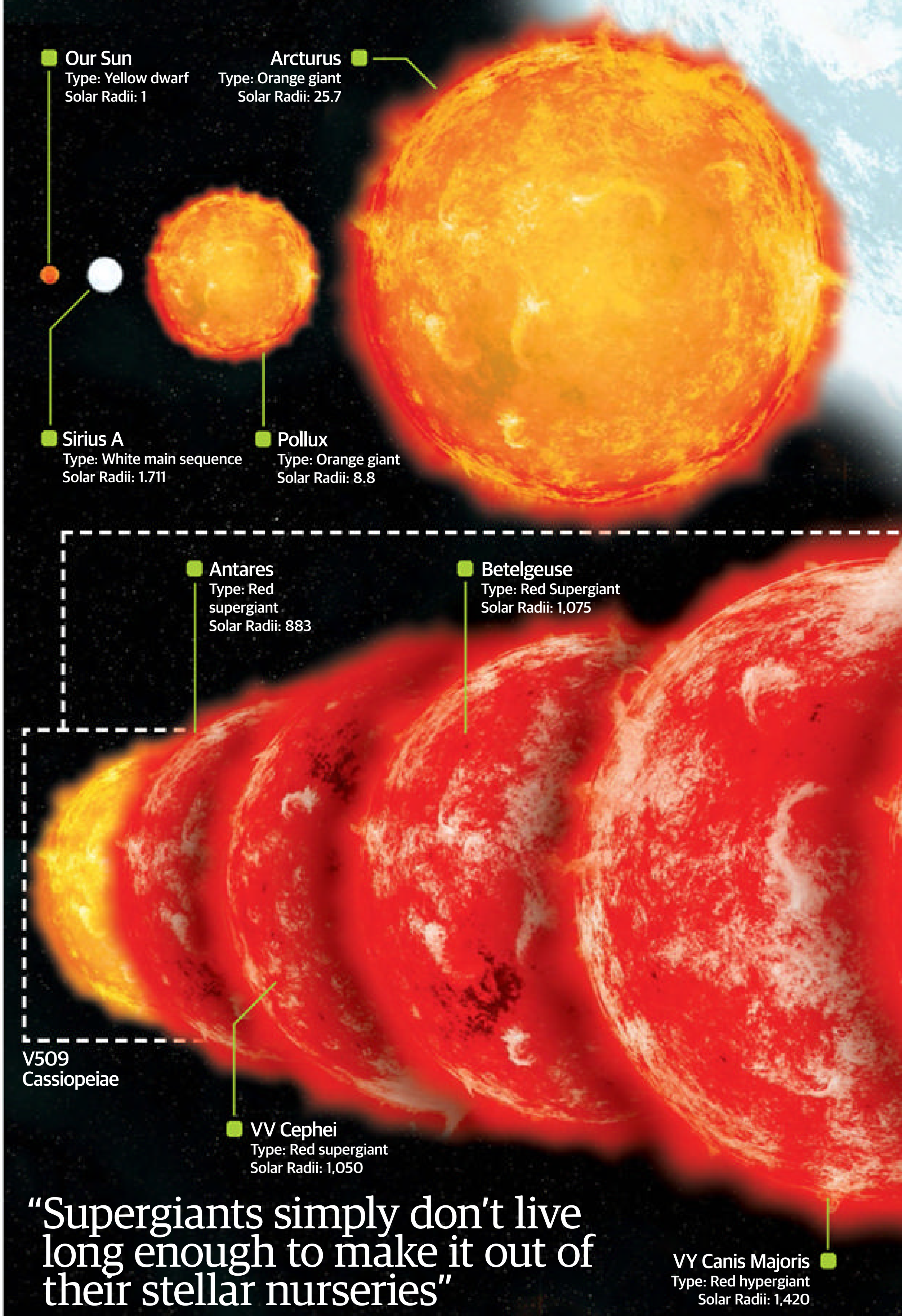
"In astronomy I think there's a natural tendency to be attracted to extremes," explains Professor Paul Crowther from Sheffield University. "Whether that's the most extreme by physical size, which are generally the cool red supergiants, or the most extreme by mass, which are the hottest and brightest blue hypergiants."

Supergiants and hypergiants were first discovered through the theoretical tools of astronomy – in particular the Hertzsprung-Russell (H-R) diagram which allows astronomers to visualise the properties of stars en masse. However, the word 'giant' can be somewhat confusing, because in this case it combines concepts of mass and size. The largest stars by diameter can all be loosely defined as 'red giants' – an evolutionary phase that most stars pass through near the end of their lives, during which they swell to huge diameters (often larger than Earth's

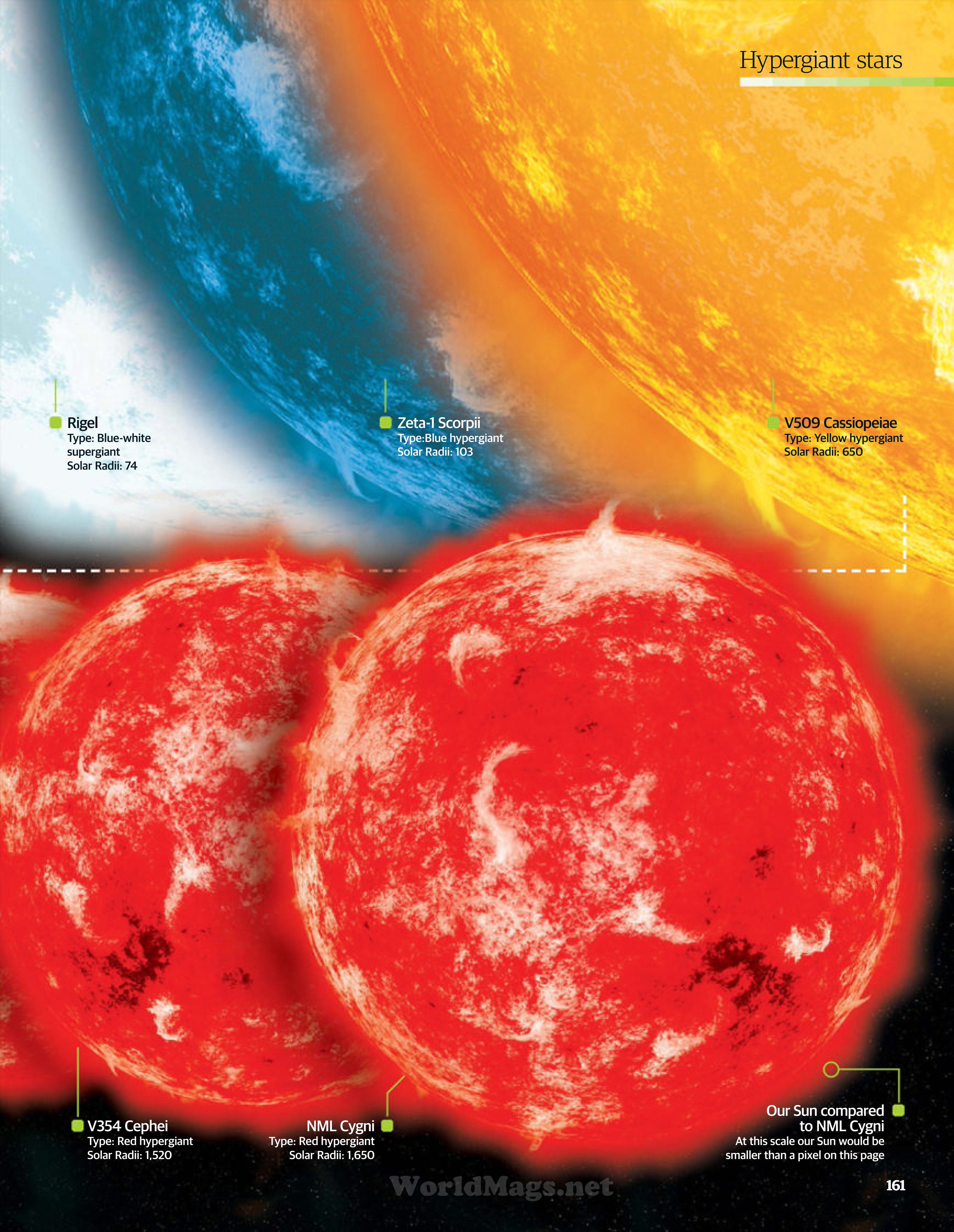


This image shows a spiral structure in the material around the R Sculptoris star

The size of stars

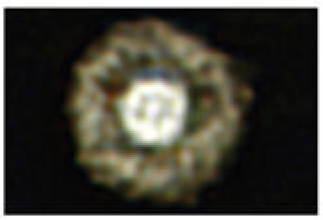


"Supergiants simply don't live long enough to make it out of their stellar nurseries"

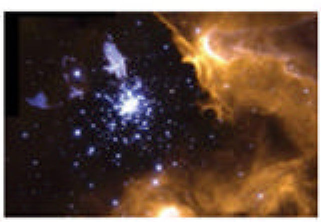

Rigel
Type: Blue-white supergiant
Solar Radii: 74
Zeta-1 Scorpii
Type:Blue hypergiant
Solar Radii: 103
V509 Cassiopeiae
Type: Yellow hypergiant
Solar Radii: 650
V354 Cephei
Type: Red hypergiant
Solar Radii: 1,520
NML Cygni
Type: Red hypergiant
Solar Radii: 1,650
Our Sun compared to NML Cygni
At this scale our Sun would be smaller than a pixel on this page

Types of giant stars

Red supergiant
The biggest red giants are the largest stars in the universe, swollen to diameters of a billion kilometres or more by changes in their cores as they near the end of their lives. As they swell in size and brighten to hundreds of thousands of times solar luminosity, their surfaces cool to a distinctive red colour. But many scientists say these stars are supergiants rather than true hypergiants.



Yellow supergiant
Yellow supergiants seem to be a rare intermediate stage, though again they get their name from their size and brightness rather than their mass. They seem to be red supergiants that have shed large amounts of their outer gas as they head towards a supernova explosion. In this photo of the 'Fried Egg Nebula', rings of ejected material can be seen surrounding the central star.



Blue hypergiant
Blue hypergiants are the real heavyweights of the universe – tens or even hundreds of times more massive than the Sun, and millions of times more luminous. Their powerful gravity limits their size, so their surfaces are intensely hot. The young star cluster NGC 3603, shown here, contains one binary system whose stars contain a staggering 90 and 120 solar masses of material.

orbit around the Sun) and become far more luminous as they pump out more energy, but conversely turn red thanks to the coolness of their vast outer surfaces. The more massive a star is, the bigger it will grow as a red giant, and red supergiants with tens of solar masses (such as VY Canis Majoris, with a diameter larger than Jupiter's orbit around the Sun) are indeed the largest stars of all. However, really monstrous heavyweight stars never actually reach this stage, so while the larger a red giant is, the more massive it will be, the most massive stars of all aren't actually the largest.

The most massive stars are born at the heart of collapsing star-forming nebulas, where gas and dust are most readily available. Unlike the more sedate, Sun-like stars, which form around the edges and coalesce over many millions of years, these stellar heavyweights grow to their enormous proportions in just a hundred thousand years. The overall amount of raw material in the nebula (reflected in the size of the star cluster that emerges from it) also has a role to play.

"There seems to be a broad relationship between the total mass of a cluster, and the most massive star within it – so for instance the Orion Nebula has a mass of 1,000 Suns,

> "The borderland between supergiants and hypergiants is filled with unusual stars"

and its most massive stars are about 30 times that of the Sun, while the NGC 3603 cluster has about 10,000 solar masses of material, and its most massive stars weigh around 100 solar masses. We don't know quite why this 'mass function' is the way it is in young star clusters, but it seems to be a universal rule," says Crowther

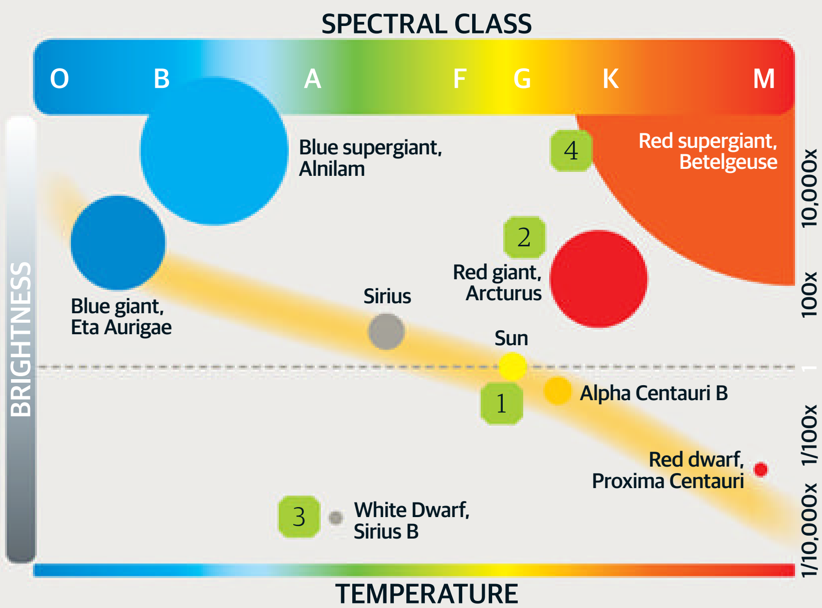
Competition between the massive central stars seems to act as a throttle to the formation process, ensuring that really massive stars are increasingly rare. "The next obvious question is whether if you had an even more massive cluster, would the mass of its biggest star keep going higher?" says Crowther. "And the answer seems to be no – we suspect there's a limit and it's linked to the star formation process. A star forms in a collapsing nebula full of competing stellar 'seeds', and it has a limited time to grab as much material as it can, or else its neighbours will. It's a bit like throwing a handful of sweets into a crowd of children – the ones nearest the centre will grab most of them really quickly, while those at the edges hardly get any. It's a competitive environment, and that probably puts an upper limit on how massive a star can get."

Another major difference between normal and monster stars lies in the nuclear reactions that keep them shining. In low-mass stars, these reactions are dominated by the 'proton-proton (p-p) chain', a process in which individual hydrogen nuclei fuse together one reaction at a time, to eventually produce nuclei of helium, the next heaviest element. The p-p chain releases small amounts of energy at every step, but proceeds relatively slowly allowing Sun-like stars to keep shining for billions of years.

In more massive stars, however, another process called the CNO cycle becomes important. This fusion chain also converts hydrogen nuclei into helium, but it uses carbon nuclei as a sort of 'catalyst', allowing the reactions to happen at a much faster rate. The CNO cycle becomes increasingly dominant at higher temperatures and densities, and causes heavyweight

Star classification

One of the most useful tools for classifying stars is the Hertzsprung-Russell (H-R) diagram. It plots stars according to their surface temperature and colour or 'spectral type' (on the horizontal axis) and their luminosity (on the vertical axis). When a large number of randomly selected stars are plotted, a pattern soon emerges: most stars are arranged along a diagonal ribbon known as the 'main sequence', that runs between the faint, cool and red and the bright, hot and blue. Luminous cool stars and faint hot ones ('red giants' and 'white dwarfs') occupy regions to either side of the main sequence and are comparatively rare.



1. Main sequence
This is the region where stars spend the majority of their lives – a star's position on the main sequence is largely determined by its mass.

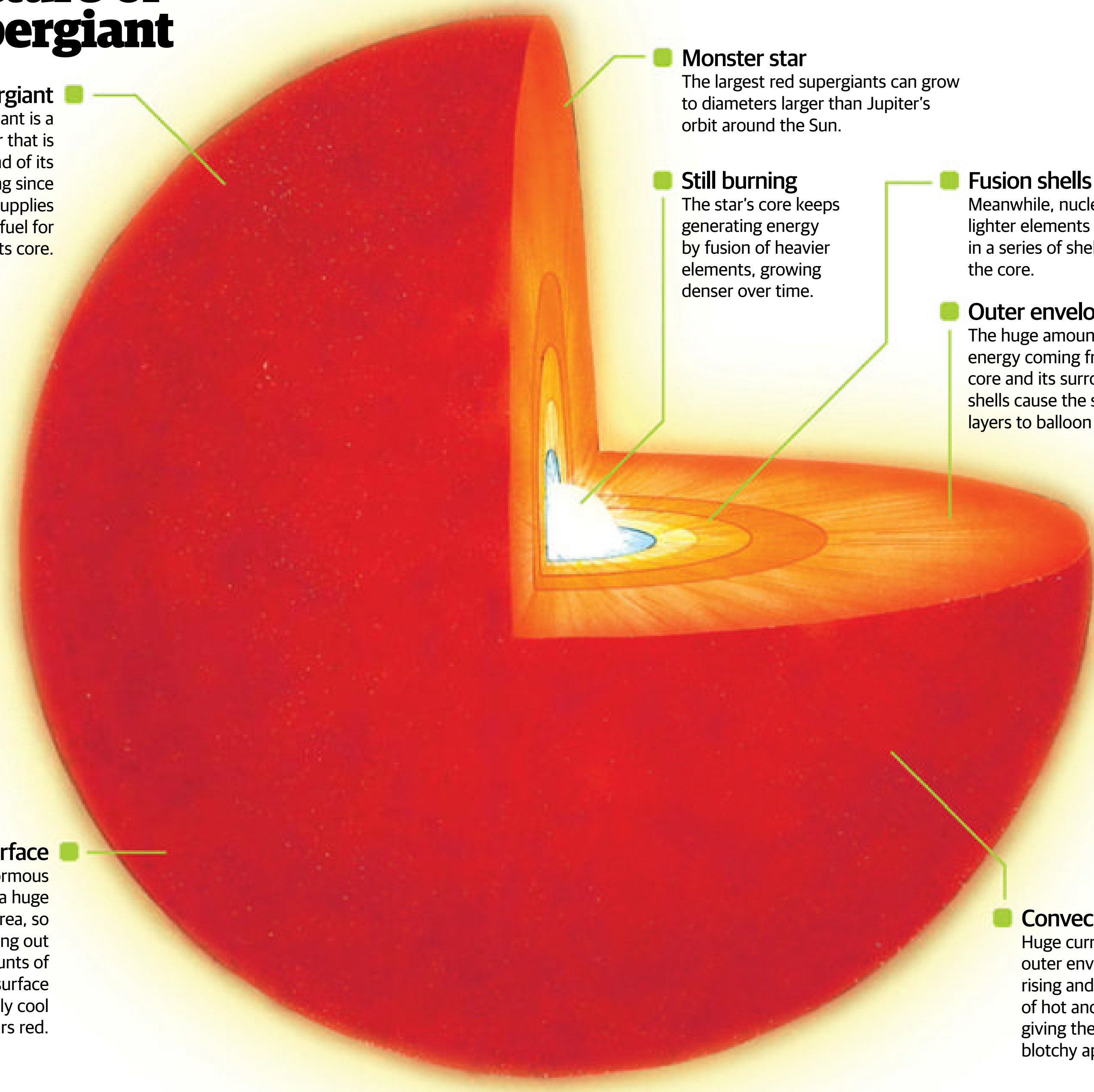
2. Red giants
Most stars pass through this phase near the end of their lives, brightening and developing an atmosphere with a cool surface.

3. White dwarfs
These hot stars are faint because of their tiny size – they are the burnt-out, slowly cooling cores of stars like our own Sun.

4. Supergiants
These high-mass stars are brilliantly luminous and display a variety of colours as they move back and forth across the H-R diagram.

Structure of a supergiant

Red supergiant
A red supergiant is a high-mass star that is nearing the end of its life and has long since exhausted the supplies of hydrogen fuel for fusion in its core.



Monster star
The largest red supergiants can grow to diameters larger than Jupiter's orbit around the Sun.

Still burning
The star's core keeps generating energy by fusion of heavier elements, growing denser over time.

Fusion shells
Meanwhile, nuclear fusion of lighter elements spreads out in a series of shells around the core.

Outer envelope
The huge amounts of energy coming from the core and its surrounding shells cause the star's upper layers to balloon in size.

Cool surface
The star's enormous size gives it a huge surface area, so despite pumping out huge amounts of energy, the surface remains relatively cool and appears red.

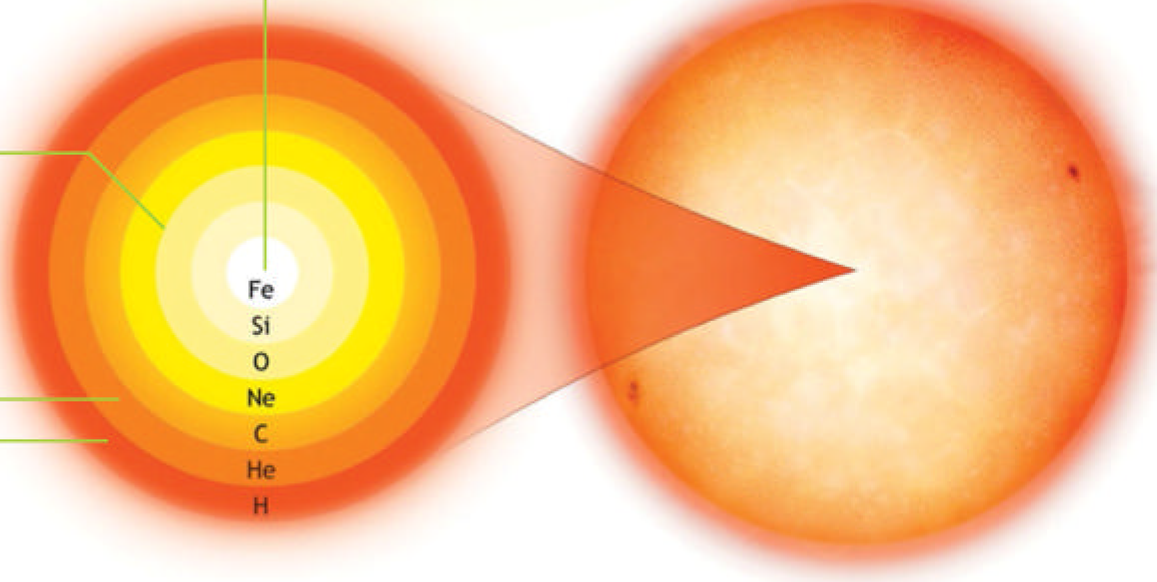
Convection cells
Huge currents within the outer envelope create rising and sinking masses of hot and cool gas, often giving the star's surface a blotchy appearance.

Iron core
Just before the star dies, a core of solid iron begins to build up. Unlike the lighter elements, iron fusion absorbs, rather than releases energy, triggering the core's collapse and a supernova explosion.

Heavier shells
Closer to the core, heavy elements continue to fuse into still heavier ones, allowing the supergiant to keep shining.

Helium fusion
A second shell of helium fusion follows the hydrogen shell out into the star, creating heavy elements such as carbon and oxygen.

Hydrogen fusion shell
Changes in the star's density and temperature allow hydrogen fusion to continue in an expanding shell around the core after hydrogen in the very centre has been exhausted.



stars to shine many thousands of times more brightly than their less massive neighbours. But the price for this brilliance is a drastically shortened life span – even though their cores contain much more nuclear fuel than those of Sun-like stars, massive stars exhaust themselves in just a few million years and begin to swell into supergiants or hypergiants.

This short life span means that supergiants are almost always found at the heart of newborn star clusters – these clusters disintegrate over millions of years, eventually scattering their longer-lived stars over a broad region of space, but supergiants simply don't live long enough to make it out of their stellar nurseries.

"These stars are incredibly rare – they only form in a few places and have very short lifetimes, so even if you find a star cluster that's just 5 million years old, its most massive stars will already have died," says Crowther. "There's only a handful of really young, massive clusters close enough to Earth for us to look for these guys and they're losing mass at a terrific rate, so the mass we measure depends on just how old the stars happen to be. The places where you usually find these really massive clusters tend to have enhanced star formation rates, usually due to galactic collisions or interactions."

So what do supergiants and hypergiants look like? They're surprisingly varied – while the H-R diagram might suggest that they'd all have extremely hot surfaces and appear blue in colour, in reality they range across the spectrum of colours. Supergiants show the most variety, and it seems that their colours simply reflect the precise balance between the inward pull of gravity and the outward pressure generated by its radiation at a particular phase in their lives. This balancing act, known as 'hydrostatic equilibrium' governs a star's overall diameter and therefore its surface area: even highly luminous stars can display Sun-like yellow, or even cooler red surfaces if they are large enough for the heating effect of their escaping radiation to be thinly spread.

Most stars retain more or less the same mass (and therefore gravity) throughout their lives, so their equilibrium is mostly affected by changes to their luminosity as the nuclear reactions in their cores change and evolve – from this, we can work out that blue supergiants are still close to the 'main sequence' of stellar evolution, while yellow ones have

Hypergiants in our galaxy

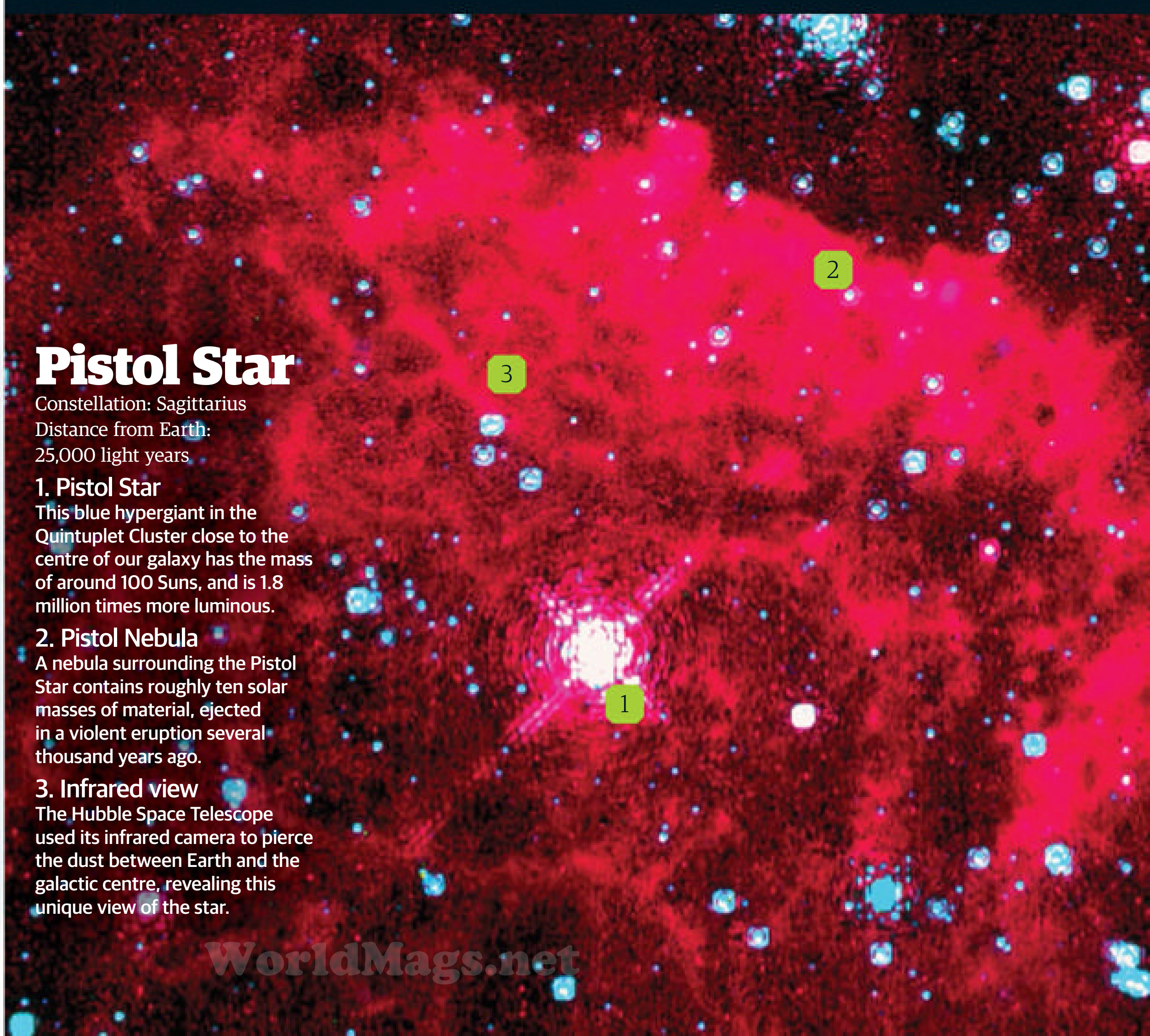
Eta Carinae

Constellation: Carina
Distance from Earth:
7,500-8,000 light years

1. Massive binary
The hypergiant Eta Carinae in the southern constellation of Carina is a binary system in which one star has at least 120 times the mass of the Sun, and is 5 million times more luminous.

2. Violent outbursts
Eta Carinae is prone to sudden eruptions that cause it to brighten unpredictably as it hurtles towards an eventual death as a supernova.

3. Homunculus Nebula
The star is still surrounded by this famous double-lobed nebula, ejected during its last major eruption around 1843.



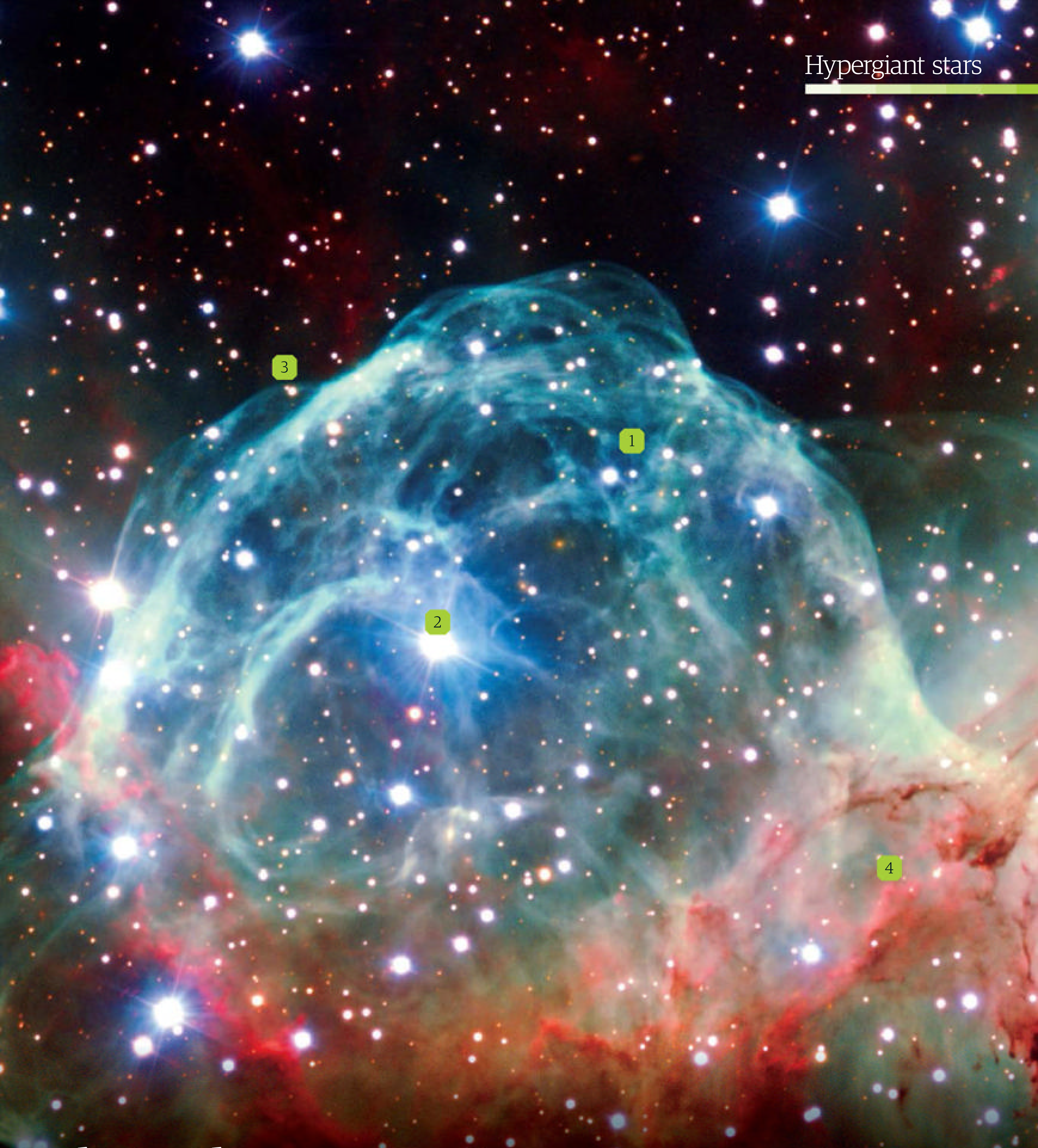
Pistol Star

Constellation: Sagittarius
Distance from Earth:
25,000 light years

1. Pistol Star
This blue hypergiant in the Quintuplet Cluster close to the centre of our galaxy has the mass of around 100 Suns, and is 1.8 million times more luminous.

2. Pistol Nebula
A nebula surrounding the Pistol Star contains roughly ten solar masses of material, ejected in a violent eruption several thousand years ago.

3. Infrared view
The Hubble Space Telescope used its infrared camera to pierce the dust between Earth and the galactic centre, revealing this unique view of the star.



Thor's Helmet

Constellation: Canis Major Distance from Earth: 15,000 light years

1. Thor's Helmet
This distinctive nebula, which is catalogued as NGC 2359, lies 15,000 light years from Earth in the constellation of Canis Major.

2. Wolf-Rayet star
The central star is a blue supergiant with a powerful stellar wind blowing material away off its surface – an object known as a Wolf-Rayet star.

3. Gas shell
As wind from the star collides with the nearby interstellar medium, it is heated and excited to release energy through light, creating a glowing gas bubble.

4. Swept wings
Collisions with interstellar material as the star travels through space create the nebula's distinctive helmet-like wings.

“R136a1 probably started its life even bigger than its current 265 solar masses”

begun to swell in size as they reach the end of their lives. Red supergiants are even further along their life cycle, and are the largest stars of all.

But for really massive hypergiant stars, there’s a different story. These stars never make it across to the red side of the H-R diagram – instead their brilliant radiation generates such huge pressure that it blows their outer layers away into space, exposing the interior and ensuring that such stars remain hot, maintaining blue or white-hot surfaces throughout their lives. This strong outflow of hydrogen-rich material gives itself away in a hypergiant’s spectrum and is one of the key means of distinguishing them from really bright supergiants.

The borderland between supergiants and hypergiants is filled with a strange variety of unusual stars, and no two astronomers really agree on the dividing lines between them. For example, luminous blue variables are extremely bright stars that show long, slow changes in brightness with occasional outbursts, and include both supergiant and hypergiant stars. Most of the rare so-called ‘yellow hypergiants’, despite their name, actually seem to be red supergiants that are shedding their outer layers and heating up. And, as we’ve seen, astronomers also differ about whether red hypergiants even exist! Depending on their features displayed in their light, other categories of supergiant or hypergiant bear exotic names such as Wolf-Rayet stars and Ofpe stars.

However, until recently, the only certain means of weighing really massive stars, and identifying supergiants and hypergiants, was to pick them out in binary systems. Here, the orbital motions of the two stars can be used to calculate their masses. Fortunately, a recent breakthrough in modelling the behaviour of really high-mass stars promises to remove some of these limitations.

Supergiant and hypergiant stars live fast and die young, but what fate awaits them at the end of their lives? Once a star has exhausted the hydrogen fuel in its core, it reaches the end of its main sequence lifetime and can only continue to shine by burning hydrogen from the shell surrounding the core, and heavier elements in the core itself. These processes cause the dying star to brighten and swell, shifting it towards ‘red supergiant’ territory, while its core develops a complex layered structure of increasingly heavy elements. Each new phase of fusion produces less energy than the previous one, and is exhausted more quickly, but the radiation that continues to pour from the core still helps to support it against its own enormous gravity.

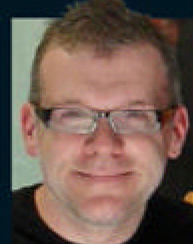
That all changes when the star attempts to fuse iron – the first element whose fusion absorbs energy. The star’s power supply falters and dies, and the huge weight of its outer layers comes crashing down. In what is known as a ‘core-collapse supernova’, the iron-rich core is compressed to a tiny size, while a tremendous shockwave rebounds through the remainder of the star, heating and compressing it until the star ignites in a blaze of nuclear fusion that may last months and outshine a billion stars. As the supernova fades and the debris clears, the compressed remains of the core may be revealed as a super-dense neutron star, or even a black hole.

For the most massive stars of all, there may be a third option. “Theorists tell us that if a star dies with roughly 200 solar masses of material remaining, it could just blow up – it wouldn’t be the usual core-collapse event, but a ‘pair-instability supernova’, which would blow itself up before it could form a super-dense core. These things would be amazingly bright and there have been a few observations of events that might be this kind of ‘superluminous supernova’.”

Astronomers believe that supergiants and hypergiants would have been far more widespread in the early universe, when the lack of heavy elements would have given them a more compact structure with a hotter surface. Thanks to the expansion of the universe, the ultraviolet radiation that poured from the surface of these stars should now be stretched or ‘Doppler-shifted’ to infrared wavelengths. Here it should be visible to NASA’s James Webb Space Telescope when it launches in 2018 to give us our first view of the earliest stellar generations. ●

R136a1 was discovered in the massive, young star cluster R136, which resides in the 30 Doradus Nebula, a turbulent star-birth region in the Large Magellanic Cloud galaxy

Searching for monster stars



In 2010, Professor Paul Crowther and his team discovered the most massive known single star, R136a1

Can we start by asking what first drew your attention to the R136 star cluster?

Well, it’s probably the prime target for anyone looking for the most massive stars – it’s the most obvious place to look really because it’s the most massive young star cluster in our part of the universe. It’s about the same size as the famous Orion Nebula, but while that’s got a couple of thousand stars, R136 probably contains 100,000 stars or more, if you could see them all. It’s been known about for a long time, but the exciting thing is that now, with Hubble and large ground-based telescopes, we can resolve separate stars and look at them individually.

As I understand it, there’s a really tight knot of stars at the cluster’s centre, called R136a?

Yes – and originally there were claims that R136a was a single supermassive

star thousands of times more massive than the Sun. But about 25 years ago astronomers confirmed that it was actually a cluster and now, thanks to technological advances, we can finally analyse the individual stars within it. When our team looked at it with the European Southern Observatory's Very Large Telescope in Chile, we were actually looking for binary stars, hoping we could use them to measure the masses of stars directly. We didn't find any binaries, but we did find that the individual stars in the cluster, and the brightest one in particular, are far more exceptional than anyone had thought.

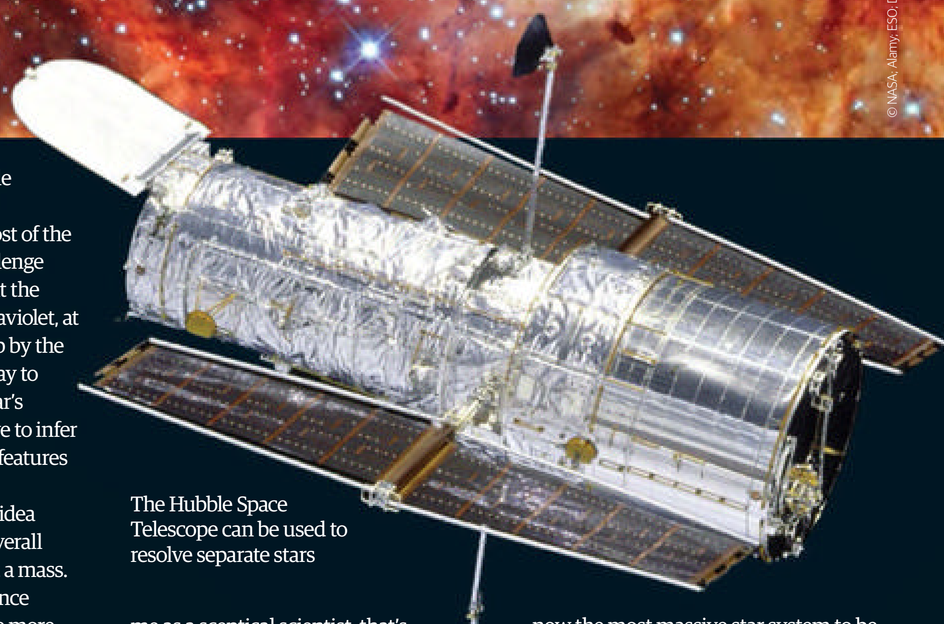
So a binary system would have let you measure the mass of its stars directly – but how do you work out the mass of a giant single star like R136a1?

The first thing you do is work out the star's luminosity, but that's a problem in itself. If you're looking at a yellow star with the same surface temperature as the Sun, then it's fairly straightforward – you're seeing most of the radiation in the optical and can work out the total energy output quite easily. Red stars such as cool supergiants emit only a tiny fraction of their energy as visible light, but you can still measure them in the infrared, where most of the energy is coming out. The challenge with hot stars like R136a1 is that the energy's coming out in the ultraviolet, at wavelengths that get soaked up by the interstellar medium on their way to Earth. We can't measure the star's peak energy directly, so we have to infer it in other ways, through other features of its light.

But even once you've got an idea of the star's temperature and overall luminosity, you still have to get a mass. Fortunately on the main sequence there's a clean relationship – the more luminous a star, the more massive it is. For R136a1, where we came up with a luminosity not far off 10 million times that of the Sun, we asked our colleagues to work out evolutionary models for the expected mass. That's how we arrived at the figure of 265 solar masses, and the star probably started its life even bigger.

And is there any way to check that theoretical result?

Well, the problem is that you're relying on one method to get a temperature, another to get a mass, and so on. For me as a sceptical scientist, that's all rather dubious – the figures are very interesting but not really backed up by enough evidence to prove it.



The Hubble Space Telescope can be used to resolve separate stars

So what we did was go looking for another example of a similar star to prove the technique. Ideally we were looking for a star in a close eclipsing binary system [where the two stars regularly pass in front of each other as seen from Earth], which would let us work out the mass independently. We eventually found just such an object in a cluster called NGC 3603, about 25,000 light years from Earth. That is now the most massive star system to be confirmed through the laws of orbital motion – it's got two stars in an orbit of about four days, with masses of 120 and 90 Suns.

Once we had got those robust numbers for that system, we used them to test our temperature and luminosity-based methods, and we got basically the right answer, which was reassuring.

So that was a sanity check – if it had worked for that object, there's no reason why the method, and of course the final result, shouldn't then also be correct for our R136a1 work.

GIANT SPACE STORMS

Witness the awesome power of Jupiter's great eye and other cosmic weather, as we chase the biggest cyclones and most extreme temperatures in the cosmos

Inside the Great Red Spot on Jupiter, as depicted by this artist's illustration

As we fight against the high winds, lashing rain and deafening thunderstorms on our planet, it's quite easy to think that there's nothing worse than the dreadful weather that can batter Earth's landscape. That is, until you leave the envelope of our atmosphere that serves as a gateway to space. Here, even a windproof umbrella and a faithful waterproof windcheater jacket that served you so well on Earth won't save you. That's because the weather that can be found in space is monstrous, making our planet's occasional crashes of thunder sound like low grumbles and the great lashes of rain, capable of flooding the lowlands, appear as nothing more than puddles made by light drizzle.

No more than an astronomical stone's throw away – at an average distance of 108 million kilometres (67 million miles) away – from our planet, things turn quite nasty on planet Venus. Nicknamed 'Earth's evil twin' with good reason, the second world from the Sun is a toxic and barren wasteland. Thick, heavy clouds laden with sulphuric acid hang in the hot, pressurised Venusian sky, topping the odd active volcano, which burp additional heat and toxicity. The scene is one of high pressures and poisonous, choking fumes, making us somewhat grateful for Earth's much more forgiving weather fronts.

In the opposite direction to Venus, things aren't much better on Mars. It's quite easy to think that nothing much happens on the Red Planet, as its robotic inhabitants – including NASA's Curiosity rover – ping back images showing stretches of barren landscape beneath a somewhat dull pink sky. The truth is, if you thought that we struggled to make an accurate prediction of the weather here on Earth, then we would be even more at a loss with the Martian weather system, leaving many weather forecasters tearing their hair out.

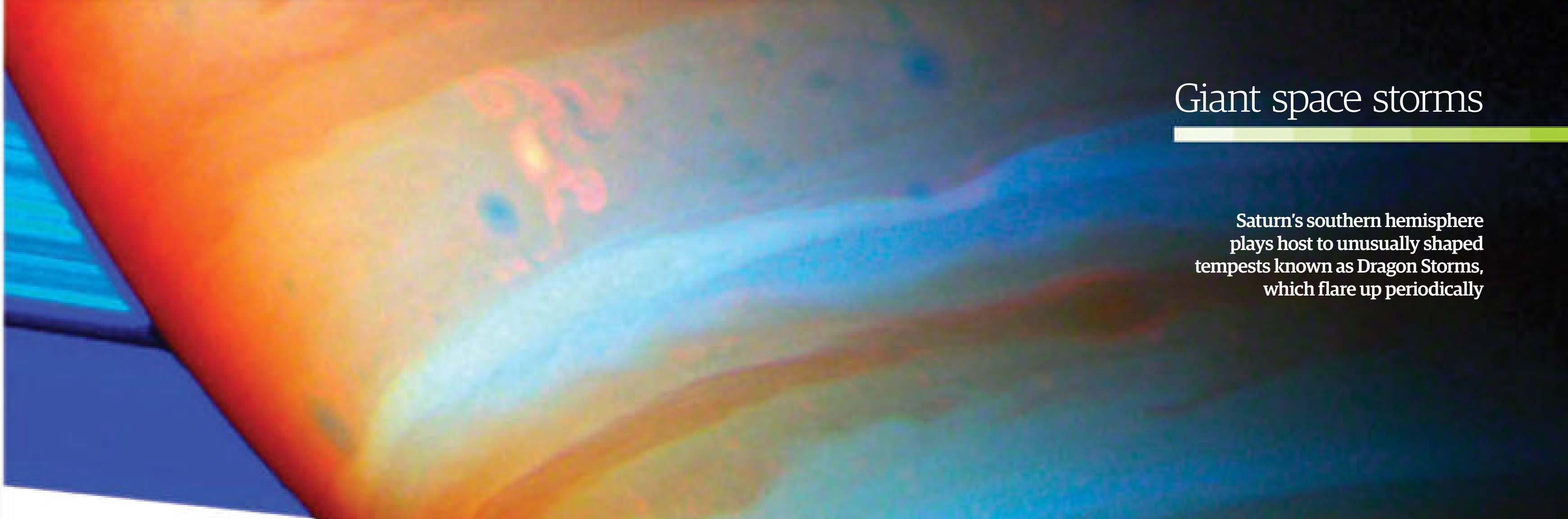
That's because Mars's weather is as unpredictable as it gets – and that's quite surprising for a planet with an atmosphere that's only about one per cent as dense as Earth's. Being so thin ensures that whoever dares to walk its dusty surface is sure to receive

"A calm day can turn into one that's rife with dust devils and great haboobs capable of engulfing the entire globe"

Saturn's southern hemisphere plays host to unusually shaped tempests known as Dragon Storms, which flare up periodically

A dust devil stalking the Martian landscape as imaged by the Mars Reconnaissance Orbiter

An artist's impression of a Martian dust storm as seen from the Viking lander



Saturn's southern hemisphere plays host to unusually shaped tempests known as Dragon Storms, which flare up periodically

fatal doses of space radiation, whether its origin is the deeper recesses of our galaxy or the Sun. There is good news, though: it never rains on the Red Planet, even though clouds do form and snow does fall, but that evaporates before it has a chance to reach the ground.

In general, Mars is pretty cold with temperatures not getting much higher than 20 degrees Celsius (68 degrees Fahrenheit), even during the summer. Day to day, or even as quickly as hour to hour, an otherwise calm day can turn into one that's rife with dust devils and great haboobs capable of engulfing the entire globe in a red haze for weeks. Kicking up such great amounts of dust is all thanks to a drop in temperature, as Martian sunsets give way to Martian nights, sending the lukewarm world's summer plummeting into a harsh -140 degrees Celsius (-220 degrees Fahrenheit).

Such a change in temperature drives hard and fast winds, which blow red dust up to speeds of over 160 kilometres (100 miles) per hour. The same thing happens on Earth, with moisture arming these swirling storms. But given that all there is to pick up on Mars is loose, red soil, raging storms throw dust into the air, supplying the Red Planet with a pinky-red atmosphere. With dust polluting the air, it can get warm on Mars, propelling the winds even faster and throwing more and more dust into the thin atmosphere, sometimes creating the snap and crackle of electricity in their wake. Then, just as quickly as it appeared, the storm can die down again – perhaps by blocking out the Sun's light – causing temperatures to cool and the soil that was once on a whirlwind trip around the globe to settle back down to the ground.

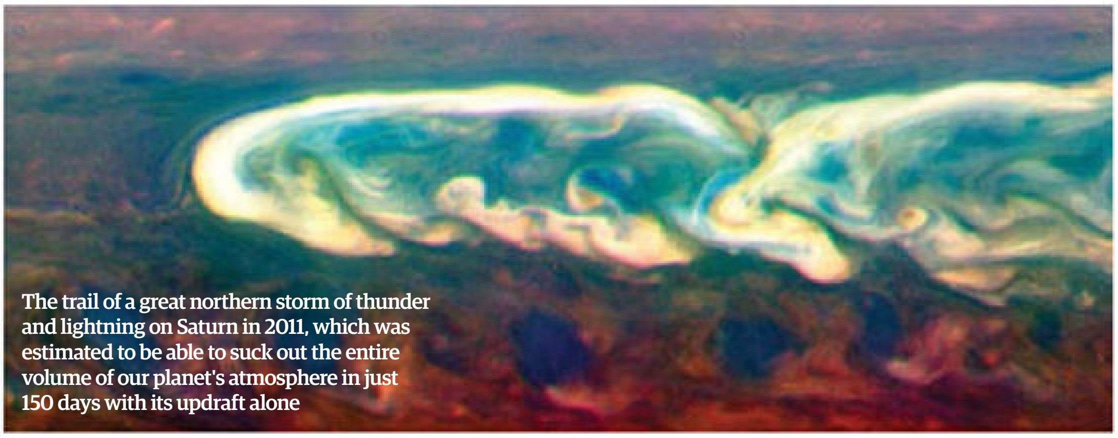
Dust storms are about as extreme as the weather gets on Mars. Trouble is, the rovers and landers that have touched down on its surface hate it. In a world of swirling dust and limited sunlight, they have no choice but to wait for the storm to be over in order to pursue their exploration of Mars as the solar panels that power them to scout the Red Planet become covered in soil.

The bigger the planet, the more heavy-handed the storms. On these giants, just a small percentage of the wind power is capable of more than blowing your umbrella inside out – it can pick up houses and throw them like dice. Surprisingly, grabbing a view of some of this weather-based action is difficult, as it can go undetected below cloud cover on some worlds.

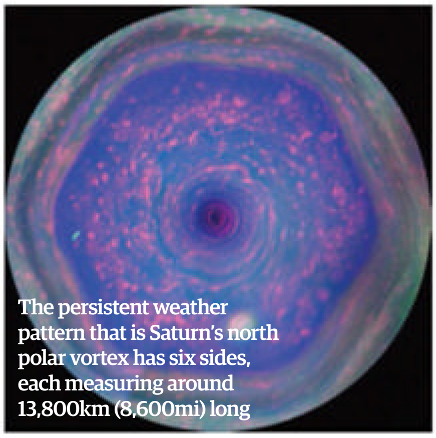
There is one planet that's not shy about showing off the forces it wields in its upper cloud layers – and that's Jupiter. Compared to the other worlds of gas that make up the outer portion of our Solar System, this majestic planetary king is a bit of a poser, proudly revealing swirls and bands that depict its chaotic nature. The most famous of these is the Great Red Spot, an anticyclone that's so large that three Earths are able to fit inside it. We're able to see this great storm system using Earth-based telescopes, and we've been watching in awe as the winds have raced at over 400 kilometres (250 miles) per hour for the past 350 years, rotating in an anticlockwise direction due to the crushing high pressure on the gas giant.

But inside this behemoth of a storm, things are quite a bit different. At its heart, gone are the gale force winds, giving way to a more gentle breeze, but where temperatures are also a chilly -160 degrees Celsius (-256 degrees Fahrenheit). To last for as long as it has, this extreme hurricane is held together by jet streams, retaining its structure to travel multiple times around the stormy planet. However, scientists have noticed that Jupiter's trademark feature is not as great as it once was: the Great Red Spot is shrinking.

In the 1800s astronomers measured the Great Red Spot to be 41,000 kilometres (25,500 miles) across. By 1979 when the Voyager 1 and 2 spacecraft reached the gas giant, the massive storm had been whittled down to around 23,300 kilometres (14,500 miles) across. Much more recently, NASA's Hubble Space



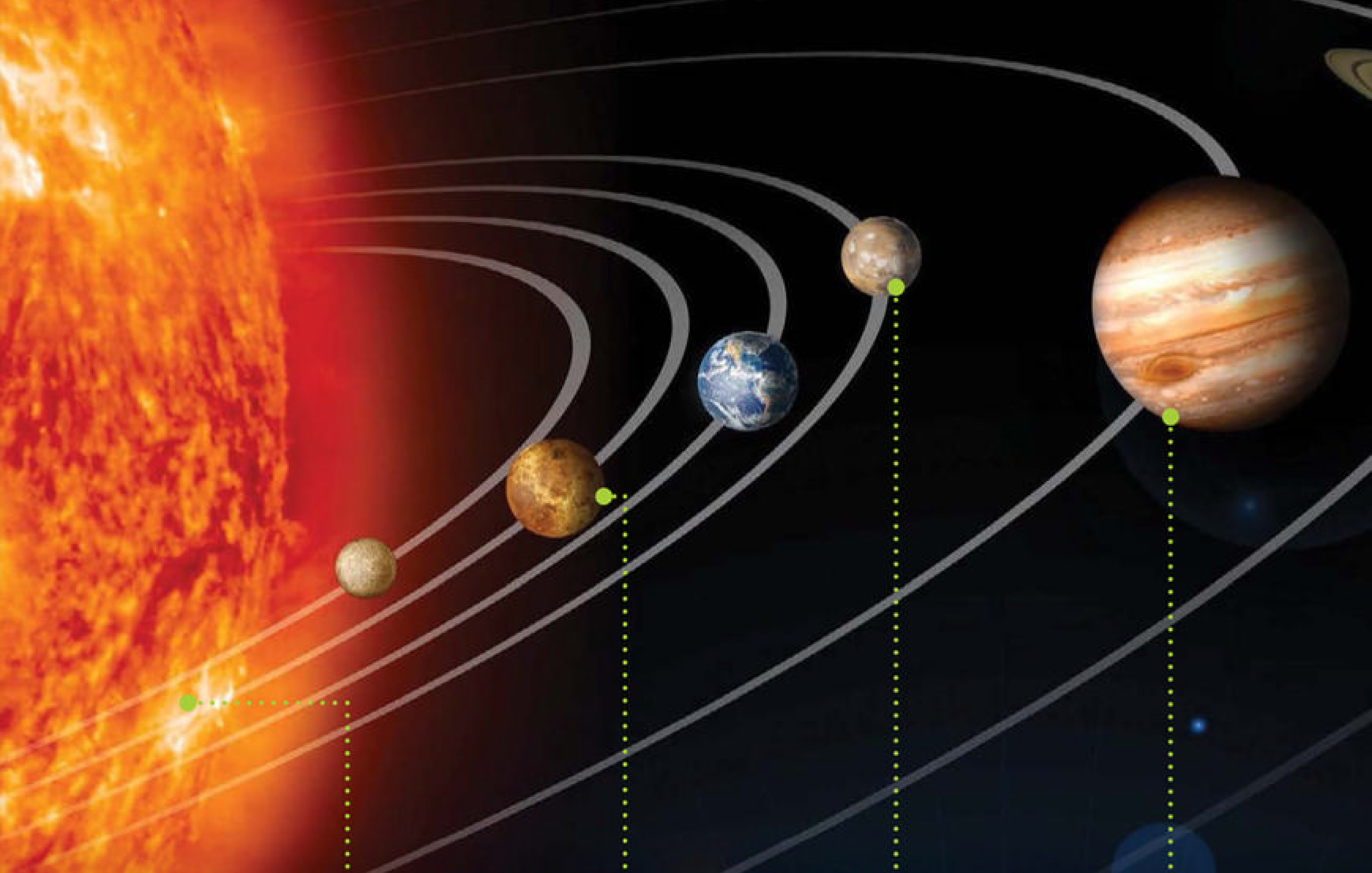
The trail of a great northern storm of thunder and lightning on Saturn in 2011, which was estimated to be able to suck out the entire volume of our planet's atmosphere in just 150 days with its updraft alone



The persistent weather pattern that is Saturn's north polar vortex has six sides, each measuring around 13,800km (8,600mi) long

The Solar System's weather

If you thought Earth's weather was bad, here's the forecast for the other worlds in our Solar System



The Sun

Extremely hot, with angry outbursts of coronal mass ejection – a massive burst of solar wind and magnetic fields. High temperatures will persist for the foreseeable future with the possibility of solar flares.

Average temperature
5,500°C (9,932°F)

Venus

A very cloudy start with acid rain only affecting the planet's highlands. There are likely to be strong winds, hitting speeds up to 360 kilometres (224 miles) per hour. High temperatures guaranteed.

Average temperature
462°C (864°F)

Mars

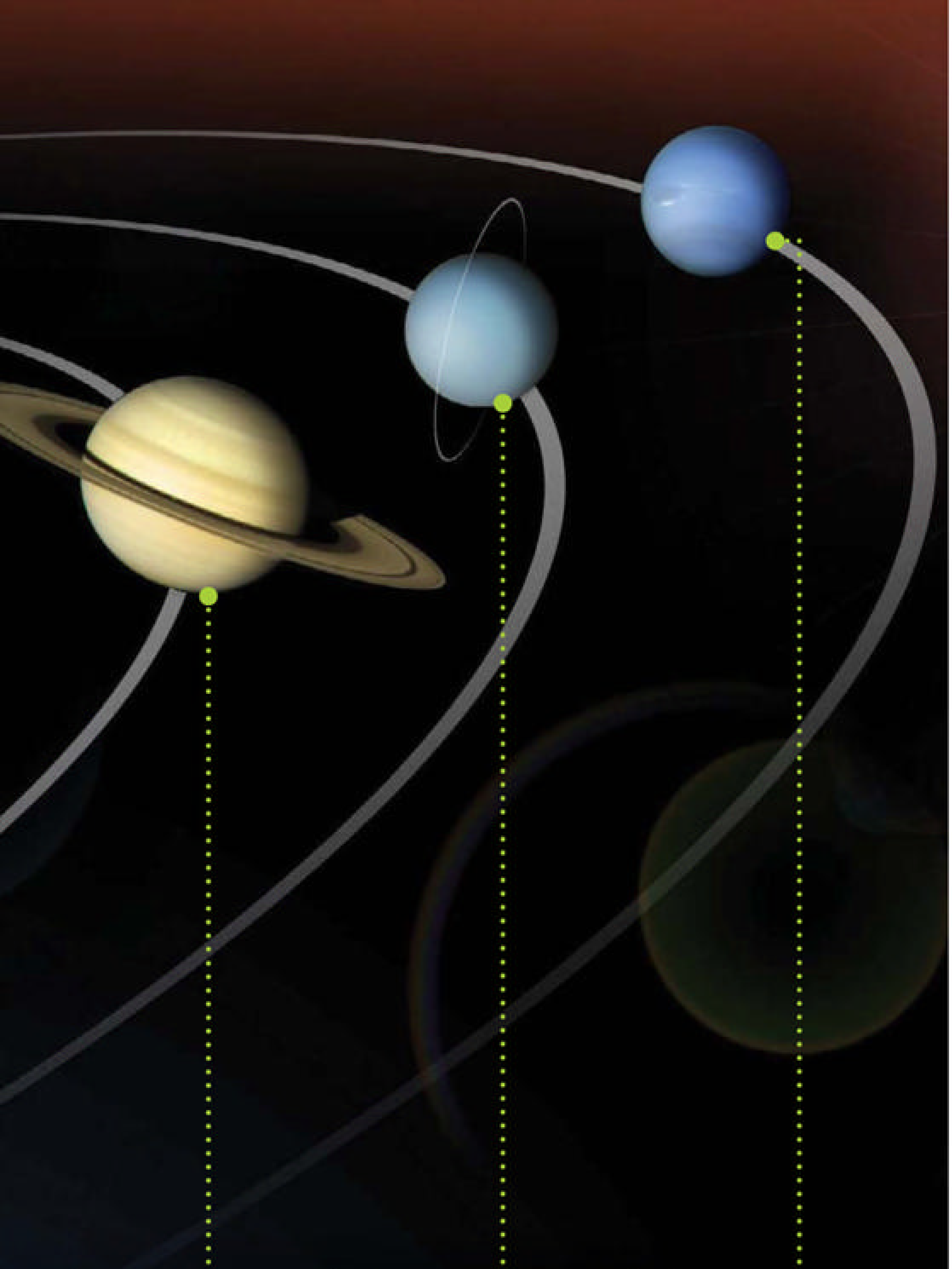
Generally cold, dry and clear all day. A change in temperature could see dust devils and dust storms become prevalent in the evening. Very cold during the night, with sub -60°C (-76°F) temperatures.

Average temperature
-55°C (-67°F)

Jupiter

Very strong persistent winds of around 360 kilometres (224 miles) per hour in most places on the globe and especially around the Great Red Spot area. Likely to be very cold all day.

Average temperature
-150°C (-238°F)



Telescope has measured the Great Red Spot to be 16,500 kilometres (10,250 miles) wide. What's more, the storm seems to be taking on a more circular appearance these days. Just what will happen to the storm next is anyone's guess, with astronomers wondering if it will vanish completely.

Jupiter's not the only planet in the vicinity to have a rampant weather system. Its neighbour, ringed Saturn, also has a huge weather system, although you'd be hard-pressed to see it from Earth. On the whole, its gaseous surface looks pretty bland, almost as if the winds and great powerful lightning bolts thrown from its cloud decks are non-existent. But underneath that creamy and misleading atmosphere, Saturn is fairly wild. Gusts topping 1,800 kilometres (1,118 miles) per hour race and force this world's collection of gases and ices around it at break-neck speed, making Jupiter's Great Red Spot seem like a light gust of wind. Up close and personal though – and with the helping hand of a fleet of space telescopes – we can get a good look at what makes Saturn's storms so mega. At the planet's north pole circulates a hexagonal storm with its six sides each measuring a whopping 13,800 kilometres (8,600 miles) long and making our planet look fairly small. To look at, this unusual anticyclonic disturbance seems unreal but it's undeniably present, with proof from the likes of NASA's Voyager and Cassini spacecrafts thrusting photographic evidence into the hands of astounded scientists.

The hexagon has bemused planetary scientists, but it seems to be some form of jet stream created by an area of turbulent atmosphere. Inside the hexagon is a whirlpool of air, which is matched at the south pole too and also on Saturn's hazy moon Titan – the only moon in the Solar System with a substantial atmosphere. On Titan, winds struggle to reach much of a pace blowing at just a few kilometres per hour as they battle through the dense nitrogen atmosphere, while it rains droplets of black methane that settles into rivers and lakes. If you were to take a tour of this moon, you would definitely need your umbrella and your thermals: it's bone-chillingly cold at -180 degrees Celsius (-292 degrees Fahrenheit).

Heading out of the Solar System at around 2.9 billion kilometres (1.8 billion miles) away, we hit the featureless face of the seventh planet from the Sun, Uranus. This collection of gas and ice might look like a boring world but underneath that placid turquoise cloud layer, a whole different story unfolds, even if it's not as enraged as the other planets we've met so far. Beneath its clouds, scientists think that it might actually rain on Uranus but we're not talking water like Earth or liquid organics like Titan – experts are hinting at diamonds. It's a jeweller's paradise, but perhaps not a rainstorm that you'd want to get caught in when it's in full force. An umbrella won't help you here either, you would need a shield, as priceless chunks rain from the heavens, making any painful hailstorm that you've been caught up in seriously pale in comparison. This torrent of diamonds – or crystallised carbon – is made by methane, being squashed under enormous pressures, hundreds of thousands of times greater than those on Earth.

They say that you shouldn't judge a book by its cover and Uranus is no exception – even if it does

Saturn

Winds hitting at least 1,600 kilometres (994 miles) per hour will make the air feel very cold wherever you are in the planet's atmosphere due to windchill. Very strong electrical storms forecast.

Average temperature
-168°C (-270°F)

Uranus

Storms possible with a chance of diamond rain, which will become heavy and persistent. Upper atmosphere is likely to be calm but on the whole, there will be high pressure and cold temperatures.

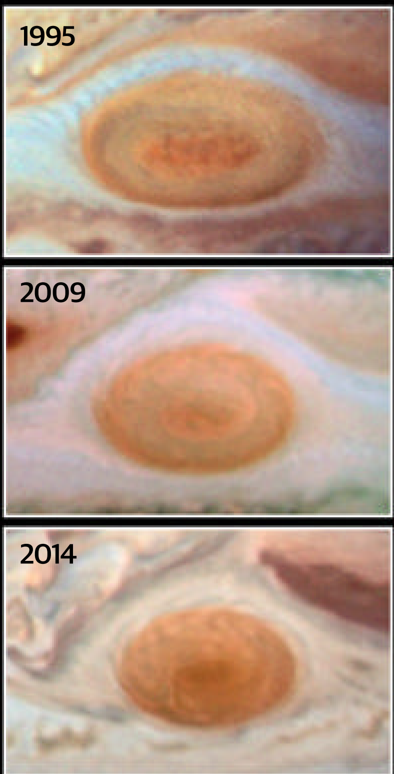
Average temperature
-224°C (-371°F)

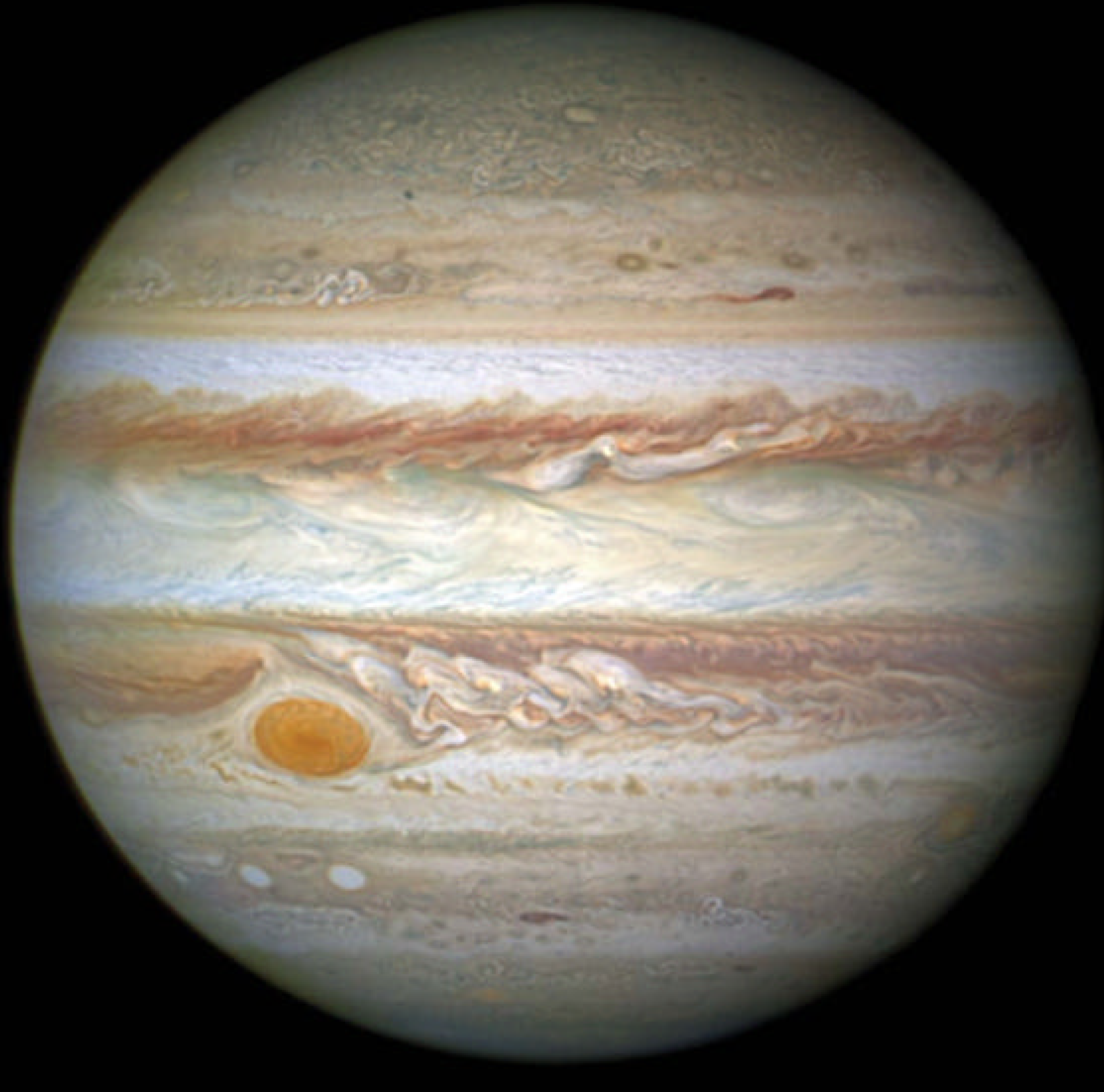
Neptune

Very blustery with diamond rain forecast. Very cold with temperatures dropping to as low as -214°C (-353°F) at times. Winds will become stronger and very persistent throughout the day.

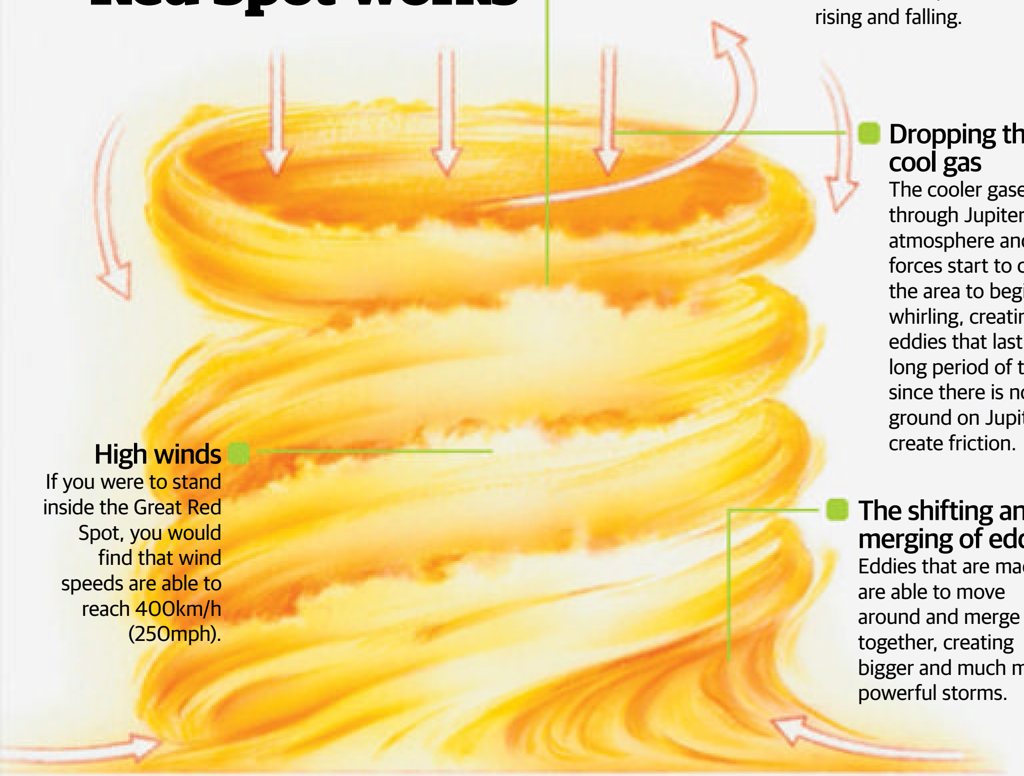
Average temperature
-200°C (-328°F)

According to observations made by NASA's Hubble Space Telescope, Jupiter's iconic Great Red Spot is shrinking in size and will continue to do so as years pass by





How the Great Red Spot works



Constant spinning
Hot gases in the gas giant's atmosphere are in a constant twirl, continually rising and falling.

Dropping the cool gas
The cooler gases fall through Jupiter's atmosphere and then forces start to cause the area to begin whirling, creating eddies that last for a long period of time since there is no solid ground on Jupiter to create friction.

High winds
If you were to stand inside the Great Red Spot, you would find that wind speeds are able to reach 400km/h (250mph).

The shifting and merging of eddies
Eddies that are made are able to move around and merge together, creating bigger and much more powerful storms.

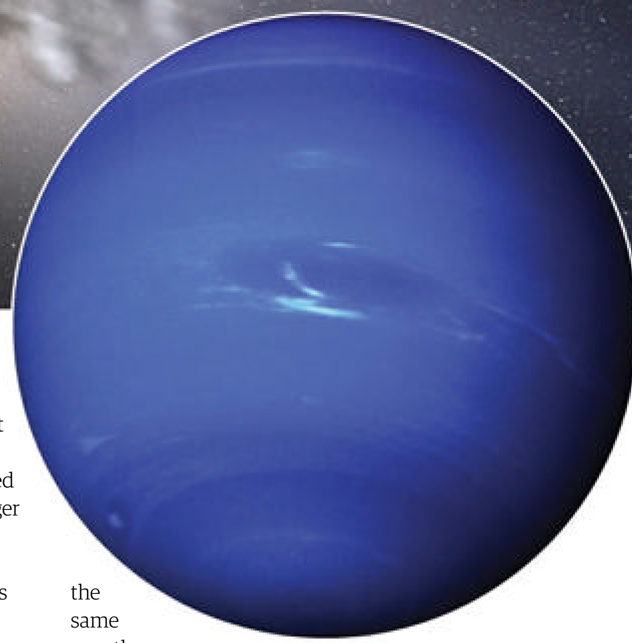
appear serene with very little activity other than the occasional angry outburst.

Fellow ice giant Neptune is outwardly much more interesting than Uranus. It too has diamond rain deep inside, but the smallest of the outer planets also tries to emulate its bigger brother with its own great spot. Here, instead of Jupiter's embarrassed red hue, Neptune's is cool and dark. It was discovered in Neptune's southern hemisphere when Voyager 2 flew past the last planet from the Sun in 1989 and is an anticyclonic storm like Jupiter's Great Red Spot, and about the same size as Earth at 13,000 kilometres (8,100 miles) across. White cirrus clouds form around its fringes, made from crystals of frozen methane. Yet while Jupiter's eye is shrinking, Neptune's spot did its own vanishing act in 1994, disappearing completely when the Hubble Space Telescope looked for it. However, this magic act was not permanent, as a new dark spot sprang to life in Neptune's northern hemisphere and is still blowing today at 2,400 kilometres (1,500 miles) per hour. Even faster clouds have been seen on Neptune, called scooters because they scoot around Neptune far faster than the lumbering dark spot.

Everything in the Solar System, even as far out as Neptune, experiences the effects of the Sun's weather. The solar wind doesn't blow air like on Earth or Jupiter or Titan, but streams of particles that wash out of our star. Occasionally the Sun burps, and unleashes storms of plasma from active regions with sunspots that can batter our magnetic field and atmosphere, generating the beautiful aurorae that illuminate the poles of our planet. These storms though can also be deadly, for the radiation can kill

A gigantic reservoir of water, which astronomers know to be quasar APM 08279+5255 holds 140 trillion times the mass of water in Earth's oceans

Ice giant Neptune is home to anticyclonic storms, which appear as dark spots and then vanish



astronauts, short-circuit satellites and knock out communications and power systems on the ground. For these reasons the Sun's weather is the most scrutinised outside Earth, with many Sun-watching space missions such as NASA's STEREO and the joint NASA-ESA mission SOHO, giving early warning of any solar storms that may be heading our way to cause mischief.

Our Sun is just one star, but what about a galaxy of hundreds of billions of stars? Their winds can combine into super winds that can blow all the gas used for making stars out of a galaxy, dispersing it many thousands of light years away. There are also storms at the centres of galaxies with giant lightning bolts that even Thor, the Norse God of Thunder, would be impressed by. In the distant galaxy IC 310, which is 260 million light years away, astronomers have detected huge bursts of gamma-ray radiation coming from enormous flashes of lightning emitted by the hot gas encircling the forbidding black hole at the centre of the galaxy. In this gas are powerful electric fields that can unleash electrical discharges every few minutes across an area of space the size of our Solar System, dwarfing all the weather familiar to us from our planetary neighbours.

On Earth, lightning is assisted by moisture in the atmosphere, and huge amounts of water have been detected as vapour in the gas around supermassive black holes. Galaxies with active black holes that are hungrily consuming gas and producing brilliant light are called quasars. In 2010, US astronomers announced the discovery of the oldest and most massive cloud of water vapour ever seen in a quasar, 12 billion light years away, which existed less than 2 billion years after the Big Bang. Far bigger than any cloud on Earth, it contains 4,000 times more water than the total found in our Milky Way galaxy. This will probably never make it into oceans or rivers, or fall as rain on a planet, but will most likely fall into the black hole instead.

There is more weather in our own galaxy besides the weather on the planets of our Solar System. The stars in our galaxy have their own planets, including a particular breed that like it especially hot. Take Jupiter with its Giant Red Spot, move it 770 million kilometres (480 million miles) closer to the Sun and you get a 'hot Jupiter'. Astronomers have found hundreds of these hot Jupiters around other stars – and they are scorching, with temperatures as great as 3,200 degrees Celsius (5,800 degrees Fahrenheit) in the case of the exoplanet WASP-33b, which is so close to its star that its year lasts just 29 hours. The close proximity to their parent star means that they're 'tidally locked' by gravity, so that they rotate at the same speed that they take to orbit their star. This means they always show the same face to their stars, the same way the Moon's face is always the same as seen from Earth. Because of this, the dayside of worlds like WASP-33b are always in their star's light, causing huge storms to arise, bigger than anything in our Solar System. The hot Jupiter exoplanet HD 189733b has a huge storm on its dayside, practically the size of its sun-facing hemisphere, where temperatures directly underneath the sun reach as much as 1,500 degrees Celsius (2,730 degrees Fahrenheit). This creates winds that outpace anything in our Solar System at 9,700 kilometres (6,000 miles) per hour, whipping around the dark side of the planet, which always faces away into space and never sees the light of its star – a dark and windy place, but never cold.

We often view the weather as an inconvenience, soaking us with rain, blowing our hair around with wind, frying us in hot and sunny climes and freezing us when snowflakes drift downwards. But when we are complaining about what the weather is doing here, spare a thought for the places experiencing far worse, not just within the confines of our Solar System but beyond it too. ■

"Astronomers have detected huge bursts of gamma-ray radiation from flashes of lightning around a black hole"